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VOLUME XIV NUMBER 4

THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED BY

EDWARD L. NICHOLS

ERNEST MERRITT, and FREDERICK BEDELL

LXXIV

APRIL 1902

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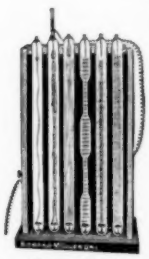

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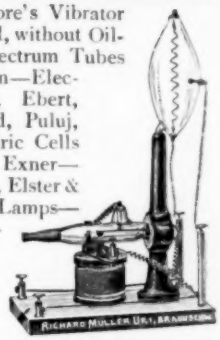

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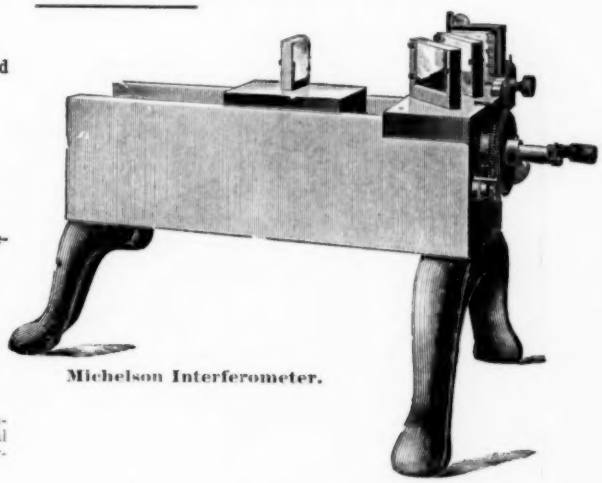

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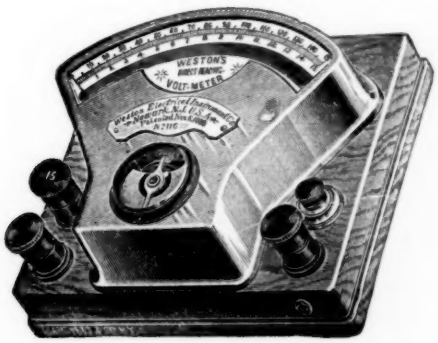

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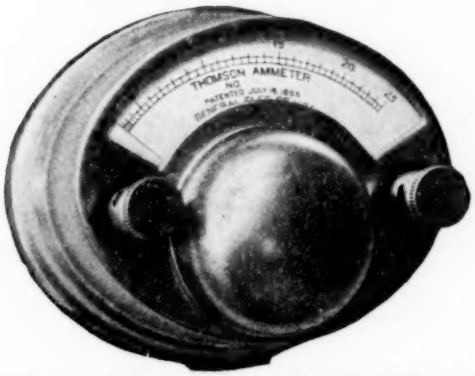

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THE

PHYSICAL REVIEW.

THE SPECIFIC HEAT OF SOLUTIONS. III. A FORM OF THE PFAUNDLER CALORIMETER.

By William Francis Magie.

1. In the course of my investigation of the specific heat of solutions[1] the calorimeter which was employed in the earlier work has been considerably modified and improved. As I expect to use the instrument in its present form in the future, it may not be superfluous for me to present a brief description of it, with an account of the method of using it and of the results which can be obtained with it. In the somewhat tedious course of experimentation by which this form of the instrument was worked out, I have been greatly indebted to Mr. Frederick Fisher, the mechanician of the John C. Green School of Science, who has aided me by his practical skill, and has furnished many valuable suggestions.

2. *The Calorimetric Method.*—The general plan of the instrument is that first proposed by Pfaundler.[2] The liquid to be examined and the standard liquid are contained in two similar vessels, and are heated by the same electric current in two coils of equal resistance. The specific heat is then determined from the observation of the rise of temperature in each vessel. In the study of solutions, the solvent is made the standard liquid. It is then possible to use such amounts of the solution and of the standard that the rise of temperature shall be nearly the same in each vessel. When this is the case the two most important corrections in most calorimetric work, that involving the water equivalent of the calorimeter and that

[1] This Review, Vol. IX., No. 2, Aug., 1899; Vol. XIII., No. 2, Aug., 1901.

[2] Wien. Acad. Bericht, Vol. LIX., 1869.

depending on radiation, are practically eliminated, if only the two vessels are alike in mass, in shape, and in character of surface.[1]

3. *The Calorimeter.*—The calorimeter vessel is a cylindrical cup, 6 inches high and 4 inches in diameter, made of thin sheet silver. It is furnished with a cover of fairly thick sheet brass, that fits snugly with an exterior flange over the top of the cup. Through the center of the cover passes a brass tube, projecting three fourths of an inch above the cover and 1 ½ inches below it. Within this is fitted a glass tube, the ends of which were shrunken a little in the flame of a Bunsen burner, and then ground and polished on the interior so as to furnish the bearings for the shaft of the stirrer. This shaft is a silver rod, provided above the upper bearing with a small pulley, and projecting below the cover 5 ½ inches. On the lower end is forced a cubical block of silver. Into slots cut diagonally in the surfaces of this block are forced rectangular silver plates $1\frac{1}{16}$ inches long and ⅝ inch wide. The paddle or stirrer thus formed is held in place by the pulley above and by a collar below its bearings. When it is turned at the usual rate it rotates about four times a second, and stirs the liquid vigorously.

In a line ½ inch from the center of the cover are placed three short brass tubes. The two end ones are 1 ½ inches apart, corresponding to the distance between the mercury cups of my Carey Foster bridge. They are fitted with rubber bushings through which pass stout copper wires, the upper ends of which carry removable binding screws. These wires within the cup are bent out and down again, so that in the cup they are 2¾ inches apart. They terminate 3 inches below the cover, where they are attached to the ends of the heating coil. This is a spiral ⅝ inch in diameter of about 40 turns of a special German Silver wire, furnished me by Mr. Edward Weston. It has a resistance of 4 ohms, and is characterized by its small or negligible temperature coefficient. This spiral is opened in the middle and held down nearly to the stirrer by a glass tube fitted in the middle one of the three brass tubes in the cover. The most convenient way to arrange this tube is to heat the lower end,

[1] These features of the instrument have been recognized by Stroud and Gee, who have described a method which is essentially the same as the one here described. El. Rev., 21, p. 262; Nature, Vol. XXXVI., p. 483. 1887.

pinch it flat, and make a small notch in the flat end. The wire is caught in this notch, and may be held there by the insulating coating.

It may be worth mentioning that it is convenient to drill the holes in the ends of the copper wires, in which the heating coil is soldered, diagonally through, so that the adjustment of the coils to equal resistance may be made without cutting the wire.

Two other tubes, 1 ¼ inches long, and of such a diameter that they will admit the thermometers used, are placed in line with the center of the cover and the tube carrying the glass rod. Their centers are ¾ inch from the edge of the cover. The thermometer is ordinarily borne in the one that is more distant from the heating coil, and the other one, which is generally stopped with a cork, is used for filling the cup, though it also receives a thermometer when the two thermometers are to be compared with each other.

The heating coils and the copper wires are coated first with asphalt varnish and then with ozokerite. Neither of these insulators could be used alone, and rubber and gutta-percha were tried also without success. The inner side of the cover and those portions of the brass tubes which project below it are coated with a thin sheathing of rubber dissolved in naphtha, to prevent possible conduction across the cover when it is covered with moisture by condensation.

Each of the cups thus constructed is set upon a network of fine cord within a cylindrical vessel of brass, 8 inches high and 6 inches in diameter, and is centered by three adjustable wooden pegs. These brass vessels or shields are placed about 4 inches from each other within a wooden box, with a cover made in two parts and cut so that the thermometers can project through it; the parts of the lid can be removed and replaced without disturbing the instrument. The conductors for the electric current enter through holes in the ends of the box. I am not sure that it would not be better to dispense with the box, when the temperature of the room can be kept constant. Thomsen[1] found it to be so; but the temperature of my work-room is so changeable that it is probably safer to protect the cups from outside changes of temperature, and to expose them only to those changes which they cause themselves. These at least are regular and similar in all observations.

[1] Pogg. Ann., Vol. 92, p. 34; Thermochem. Untersuchungen, Vol. I., p. 22.

On either side of the box rises a wooden upright sustaining a crosspiece, on which are fastened small wooden blocks, grooved to receive the upper ends of the thermometers. When the cups are in position, the thermometers are held in place in these grooves by stout brass springs. In appropriate positions are fastened to the crosspiece the magnets and circuit-breakers of two small electric bells, the hammers of which have been replaced by longer handles carrying on their ends small corks. The magnets are actuated by a pair of Edison-Lalande cell, and when in action the cork hammers keep up a lively tapping on the tops of the thermometers. The contact-maker used with this circuit is fixed in a convenient place on the side of the box.

The paddles are turned by a belt passing over both of their pulleys and over a 4-inch pulley carried on an offset in front of the box. The belt enters the box through two notches in the front, into which it falls when the front part of the cover is not in place. To admit of this the front part of the cover is made removable and is not hinged like the back part. The belt is a rubber cord about ⅛ inch thick.

4. *The Cooling Vessels.*—Before beginning an observation it is necessary to cool off the cups to some temperature below that of the room. This is done in cylindrical vessels 8½ inches in diameter and 6 inches high. Within these are placed cylinders of coarse wire netting, held in place in the vessels by three projecting arms. They are ust large enough to admit the cups, which rest on cross-pieces of wood about an inch from the bottom. The space outside these cylinders is packed with broken ice or with snow, and the vessels are filled about half full of water. When the charged cups are placed in position in these coolers, the paddles may be turned with the fingers sufficiently to bring about a regular fa ll o the thermometers, and after a little experience the cups can be removed so that the temperatures indicated after the cups have been wiped dry do not differ by more than two or three hundredths of a degree. If they differ by more than that, it is easy to equalize them by warming one of the cups with the hand.

5. *The Current.*—The current for the heating coils is furnished by a dynamo machine or a storage battery. It is led into the box

by stout copper wires, which are sufficiently flexible to admit of being pushed aside when the cups are to be removed. The connection between the cups is made by a straight piece of the same wire. The circuit contains an ammeter, a variable resistance of coarse wire, and a snap switch, placed conveniently on the front of the box. Ordinarily a current of 5 ampères is used.

6. *The Thermometers.*—The thermometers were made by Fuess. They are of Jena glass, No. 59, III., and are similar in size and shape. The graduation extends from 12° to 33° in the one and 36° in the other. A degree covers about 2 cm. and is divided directly into fiftieths. The graduation is marked in beautifully fine and even lines on a scale of opaque glass placed ust behind the thermometer tube. By the help of the reading microscopes, which are arranged to slide on the external protecting tubes, an estimate of the temperature can be made to thousandths of a degree with considerable accuracy. The bulbs are long and narrow. A short piece of rubber tubing is slipped over each thermometer and supports it at the proper height in the cup. The bottom of the bulb is brought as close as is safe to the paddle, and the upper end of it is below the surface of the liquid in the cup by 3/8 inch when 700 grams of water are used.

It is a feature of this method that the corrections of the thermometers to a standard need not be accurately known. All that is necessary is to have a comparison of one with the other. To obtain this, both thermometers were placed in the same cup, and compared at different temperatures. The curves of comparison obtained from three independent sets of observations nowhere differed from each other by more than $\frac{3}{1000}$ degree. From them a mean curve was constructed from which to correct the readings of one thermometer to the scale of the other. Since the comparison is made under the conditions of service, the corrections for stem exposure and lag are included in the results.

7. *Method of Observation.*—The course of an observation is as follows: After the cups are filled, usually with 700 grams of water and with the appropriate amount of the solution, they are placed in the coolers until the temperature falls about 5° below the room temperature (say to 15°). They are then wiped dry, the tempera-

tures being adjusted if necessary to be nearly equal, and are placed in position. At the beginning of a minute the tappers are set going, and the stirring is begun. Stirring is kept up in one sense for twenty seconds and then in the reverse sense for twenty seconds. The tappers are allowed to run five seconds longer, are then stopped, and the readings are made. This process is repeated usually twice and oftener if the differences of reading of the two thermometers show signs of a progressive change. At the beginning of a minute, after the last reading has been made, the current is thrown into the heating coils and is maintained usually for six minutes; with the current used the rise of temperature is then about 10°. During this period the stirring is continued, being changed in sense at the end of each minute. At the end of six minutes the current is cut of, the tappers set going, and readings are made as before. Nothing remains but to determine from the average temperature differences the most probable value of the rise of temperature in each cup, and to calculate the specific heat s' of the solution directly from the formula, $s' = \frac{ms\vartheta}{m'\vartheta'}$. The cups may be cooled off again and another observation made. Such an observation can be made in twenty minutes or a little over.

As an illustration we may take an observation on a $\frac{1}{200}$ milk-sugar solution. The mass of water in cup A was 700 grams, of solution in cup B was 736.57 grams. The thermometer corrections fall on the temperature in B; those due to errors in reading on that in A.

Readings.	A		Diff.	B	
		Corr. Reading.			Corr. Reading.
Before heating.	15.110		14	15.124	
	15.130	15.130	14	15.144	15.115
After heating.	25.324	25.324	−5	25.319	25.309
	25.296		−4	25.292	
	25.272		−5	25.267	
Rise of temp.		ϑ, 10.294			ϑ', 10.294

$$\frac{\vartheta}{\vartheta'} = 1.0000, \qquad s' = 0.9504$$

Heat capacity of 200 mols. water + 1 mol. milk-sugar or of 3942 grs. solution, 3746.4.
Apparent molecular heat of milk-sugar in solution, 146.4.

8. *Correction for Evaporation.*—The most important change which has been made in the construction of this instrument from that previously described[1] consists in the use of covered calorimeter cups instead of open ones. In the 25 minutes required in the earlier work for an observation, 500 mg. of water were lost from each cup by evaporation. This not only made it necessary to weigh and refill the cups after each observation, but introduced an element of uncertainty in the work that is at least partially avoided by the use of covered cups, in that any inequality in the amount of evaporation from the cups involved a considerable inequality in the amount of heat lost by evaporation. This possible difference in the amount of heat lost was included in the probable error, but it no doubt contributed to increase the magnitude of that error. Even with the covers, the evaporation is not wholly checked, as the temperature of the liquid changes, and is different from that of the cover, but it is at least rendered more uniform. In working with alcohol as a solvent or in determining the calorimeter constant with water, the first observations were always more divergent than the later ones from the mean, unless the precaution was taken to carry the temperature through its ordinary range before beginning the observations.

9. *Correction for Radiation.*—When the cups are so charged that the rise of temperature is about the same in each, the correction for radiation is negligible. This can be seen from the uniformity with which the temperatures in the cups rise or fall while the readings are being made. When the temperature changes in the cups are quite different, as in the observations for the calorimeter constant, the radiation has to be determined and allowed for. This may be done completely by determining the rate of loss of heat at different temperatures; but it is generally sufficient to judge from the differences in the temperature changes observed during the preliminary and final readings as to how much more heat one of the cups loses than the other, and to express this in terms of temperature change. This method is not suitable when the temperature changes differ greatly.

10. *Corrections for Errors in Stirring.*—In the ordinary case, the

[1] This REVIEW, Vol. IX., No. 2, August, 1899.

errors which are most difficult to control are connected with the stirring of the liquids. It is necessary to make the pulleys that turn the paddles exactly of the same diameter, and to make the paddles themselves geometrically similar; and even when they are as similar as they can be made, it is advisable to turn them in opposite senses for equal times. Even with the utmost regularity, it is not possible to be certain that the liquids are thoroughly and equally mixed, and I believe that the remaining error is more largely due to unequal mixing than to any other cause. The condition, which is important, that the paddles should extend as near the sides of the cup as possible, introduces an occasional difficulty, when the paddles, owing to imperfect fitting of the cover or to too great a strain on the belt, touch the sides of the cup. Fortunately when this happens it can usually be detected by the ear. An observation in which such a condition has existed is worthless, the heat developed by the contact being always sufficient to cause too great a rise of temperature in the cup in which it occurs.

11. *Correction for Calorimeter Constant.*—A difference in the water equivalents of the two cups may exist which must be examined and allowed for. This can scarcely be due to differences in the cups themselves, if they are carefully constructed, but may be introduced by the use of thermometers which are not sufficiently alike. The amount of this difference may be determined by a series of observations with equal quantities of water in the cups. If we represent by φ the heat capacity of the water used, by ϑ_1 the rise of temperature in cup No. 1, by C_1 the water equivalent of that cup, and use similar symbols with the subscript 2 for the quantities pertaining to cup No. 2, and remember that the same quantity of heat is contributed to each cup, we have,

$$\varphi\vartheta_1 + C_1\vartheta_1 = \varphi\vartheta_2 + C_2\vartheta_2;$$

whence

$$\varphi - \varphi\frac{\vartheta_2}{\vartheta_1} = \frac{C_2\vartheta_2}{\vartheta_1} - C_1.$$

Since ϑ_1 is nearly equal to ϑ_2, and C_1 and C_2 are small in comparison with φ, this equation gives approximately

$$\varphi\left(1 - \frac{\vartheta_2}{\vartheta_1}\right) = C_2 - C_1,$$

from which by the observations just mentioned $C_2 - C_1$ may be determined. This difference is all that is needed for correction, when the temperature change is nearly the same in each cup.

The value of the water equivalent, when it is the same for each cup, is got by using different quantities of water, so that φ_1 and φ_2 are not the same. We then have

$$C = \frac{\varphi_1\vartheta_1 - \varphi_2\vartheta_2}{\vartheta_2 - \vartheta_1}.$$

Even if the water equivalents differ, this equation will determine a value that is correct enough for use when the temperature changes are different, and the difference between the water equivalents may be got as before.

12. *Effect of Condensation.*—In the damp summer weather, the moisture which condensed on the outside of the cups, when they were cooled below the room temperature, affected the changes of temperature during the period of the initial readings, so that they were very irregular and uncertain. Successful observations could not be made at such a time.

13. *Test with Water.*—It is an advantage of this form of calorimeter that its performance can be tested by the use of equal quantities of water in the two cups. If the water equivalents and the radiation losses are the same for each, the mean ratio of the observed temperature changes should equal 1. The first set of results which follows was obtained for this case on October 10, 1901, before the laboratory was heated, and while there was a slight condensation on the cups of moisture from the atmosphere. The second set was obtained on November 9, 1901, when the laboratory was heated. The numbers given are the ratios of the temperature changes in cups A and B.

0.99987	1.00005
0.99974	1.00004
1.00004	0.99995
1.00030	1.00002
0.99963	1.00030
0.99991	
Mean, 0.99992	1.00007

The mean of both sets is 0.99999 and indicates that the correction for difference of water equivalent is negligible. In these observations the rise of temperature was over 10°. Another set of observations, in which the rise of temperature was about 3.5°, gave the following results:

	1.0003
	0.9996
	1.00025
Mean,	1.00005

Although the variations are no larger than in the other sets of measurements, and although there are good reasons for restricting the temperature change within as narrow limits as possible, yet in view of the larger effect of errors in reading the thermometers, I do not think it best to use so small a temperature change.

14. *The Calorimeter Constant.*—The water equivalent or constant of the calorimeter was determined as the mean of the following results: 700 grams of water were used in one cup, and 800 grams or 850 grams in the other.

22.6	1.0002
24.1	0.9998
24.3	1.0002
21.7	0.9997
23.4	1.0000
Mean, 23.2	

The numbers in the second column represent the specific heat of water, calculated from the observations with the mean value of the constant, and indicate the range of error when the constant is known and the difference of the temperature changes is about 1° in 10°.

15. *Examples.*—The following numbers under I. are the ratios and the molecular heats obtained from observations on a $\frac{1}{200}$ gram-molecular solution of an anhydrous form of milk-sugar. The amount of water used was 700 grams, of the milk-sugar solution 735 grams. Under II. are given the corresponding numbers for a similar solution of another form of milk-sugar. The amount of solution used in that case was 736.57 grams.

I.		II.	
0.9978	146	0.9998	145
0.9979	146	0.9999	146
0.9986	149	1.0000	146
0.9982	147	0.9997	145
0.9978	146	0.9995	144
0.9981	147	0.9999	146
0.9983	148	1.0003	147
		1.0003	147
		1.0000	146
Means, 0.9981	147	Means, 0.9999	146

The water equivalent of the calorimeter applied to such cases as those under I., where the difference between the temperature changes was about 0.02°, does not appreciably modify the results.

PHYSICAL LABORATORY, PRINCETON UNIVERSITY.

ON SOME OPTICAL PROPERTIES OF ASPHALT.

BY EDWARD L. NICHOLS.

WHEN a thin layer of asphalt varnish is spread upon glass and allowed to dry and some luminous source, such as the filament of an incandescent lamp, is observed through the film, it is found that a considerable amount of red light is transmitted, the unusual purity of which is readily ascertained by means of a spectroscope. The suddenness with which the rays beyond the red are cut off indicates the existence of a well-defined absorption band with a very steep gradient on the side toward the greater wavelengths; and one would expect to find a considerable degree of perviousness in the infra-red and anomalous dispersion in the region where the change from transparency to opacity occurs.

It is the purpose of this paper to describe some studies of this interesting substance concerning the optical properties of which nothing appears to have been recorded.

SPECTRO-PHOTOMETRIC OBSERVATIONS.

For the purpose of determining the transmitting power of asphalt in the visible spectrum, films of the requisite thickness were obtained by dipping a piece of thin plate glass into asphaltum varnish and allowing the coating to dry; after which one side of the glass was carefully cleaned. The film thus obtained covered about one half of one face of the glass plate. The instrument employed in the determination of the transmitting power of the film was a one-prism spectroscope provided with a Vierordt slit. The spectroscope was securely clamped above the table with the circle C in a vertical plane, the collimator tube horizontal, the slit horizontal and the observing telescope moving in a vertical arc. Light for the comparison spectrum was introduced through the right hand half of the slit by means of a total reflection prism P (Fig 1). The source of light was an acetylene flame (A_1) in front of which, in order to reduce the intensity, two thicknesses of ground glass (G) were interposed.

Light from a similar acetylene flame (A_2) which was mounted in the line of the collimator, entered the left half of the slit directly. The glass plate (f), with the asphalt film, was interposed in the path of this ray near the slit. By giving the plate a lateral movement of about two centimeters, the ray could be caused to pass alternately through the glass and asphalt and through the glass alone. A comparison of the absorption spectra thus obtained with the spectrum from (A_1) furnished data for computing the transmitting power of the asphalt film.

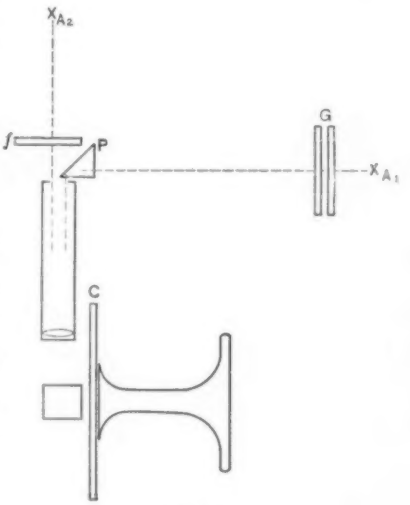


Fig. 1.

Measurements were made in five regions of the spectrum lying between .73 μ and .589 μ. The transmission of light of wave-lengths shorter than the latter was too faint to be measured. The thickness of this film, determined by measuring with a micrometer gauge the thickness of the glass and of the glass and asphalt together was found to be 0.003 cm. Table I. gives the percentage of light transmitted by the asphalt and the extinction coefficient of this substance for the regions of the spectrum in which measurements were possible.

The extinction coefficient was computed in the form used by Knut Ångström[1] with whose results with films of lampblack it was desired to compare the present measurements.

The equation has the well-known form

$$I_e = I_0 e^{-kl},$$

where I_0 is the intensity of the incident ray, I_e that of the ray transmitted by a film of thickness l and k is the extinction coefficient.

The transmission curve for the visible spectrum is shown in Fig. 2. It will be seen from these data that a film of this thickness becomes almost completely opaque in the yellow, the transmission in the

[1] Ångström, Wiedemann's Annalen, 36, p. 715 (1889).

TABLE I.

Transmission in the visible spectrum of a layer of asphalt .003 cm. in thickness.

Wave-lengths.	$\frac{I_e}{I_o}$	Extinction Coefficients[2] (k).
0.730 μ	0.0233	1256
0.680 μ	0.0088	1558
0.656 μ	0.0044	1813
0.617 μ	0.00085	2362
0.589 μ	0.00038	2631

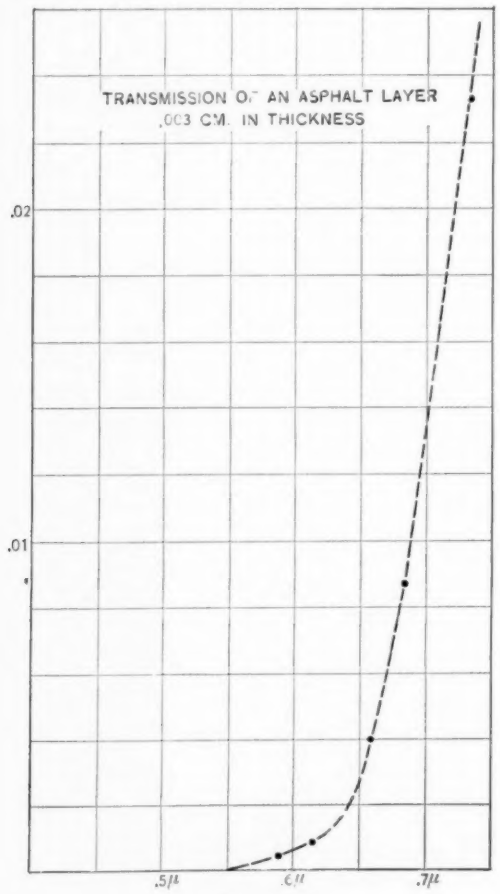


Fig. 2.

[2] To convert these coefficients into the extinction indices of Wernicke (Poggendorff's Annalen, Erg. Bd., 8, p. 67 [1877]), they must be divided by $\frac{4\pi}{\lambda}$, where λ is expressed in centimeters.

region of the D line being less than .0004 of the incident light; also that the transmission of yellow light is less than two per cent. of the transmission of the full red of wave-length .73 μ. The opacity of this film was too great to permit of the location of the position of the maximum of the absorption band and measurements were accordingly made upon much thinner layers, prepared in the following manner. A cell having the form of a hollow wedge with sides of plane glass was filled with asphalt varnish and then emptied of what could be poured out and immediately inverted and left to dry with its mouth resting upon a sheet of filter paper and the apex of the wedge uppermost.

The downward flow of the slowly drying film of asphalt gave in this case a regular gradation to the layer which at the top of the cell was so thin as to show scarcely any color, while at the bottom it was nearly opaque. The light transmitted by this cell with its double layer of asphalt at distances of 2.5 cm. and 6.5 cm. from the apex was then compared spectrophotometrically with that transmitted by an uncoated cell made of the same glass.

The color of this layer was a red, changing gradually to a pale amber, tending at the apex to a greenish yellow; indeed the variation of color with thickness might be likened to that of a dichoric liquid.

A comparison of the transmission of the two portions of these films subjected to measurement showed the substance to be optically perfect, or at least not appreciably turbid. That is to say the relation

$$\frac{n}{m}\log\frac{I_0}{I_m}=\log\frac{I_0}{I_n},$$

where n and m were the relative thicknesses in the regions measured was found to be approximately true. The ratio $\frac{n}{m}$ was determined from the distances from the apex of the wedge of the two regions, under the assumption that the films were themselves wedge-shaped, tapering uniformly towards the apex. The agreement which was at least as close as my knowledge of the relative thicknesses, was however not sufficient to establish this fact completely and measurements were accordingly made upon two layers of different thick-

nesses placed upon glass plates in a manner similar to that employed in the specimen used in obtaining the data given in Table I. The relation of transmission to thickness in this case also was found to fulfill the law for optically perfect media with a degree of approximation equal to that of my knowledge of the thickness of the films.

It was found that while each pair of films was comparable in this respect between themselves, the sets could not be compared with one another and that neither gave correct values when compared

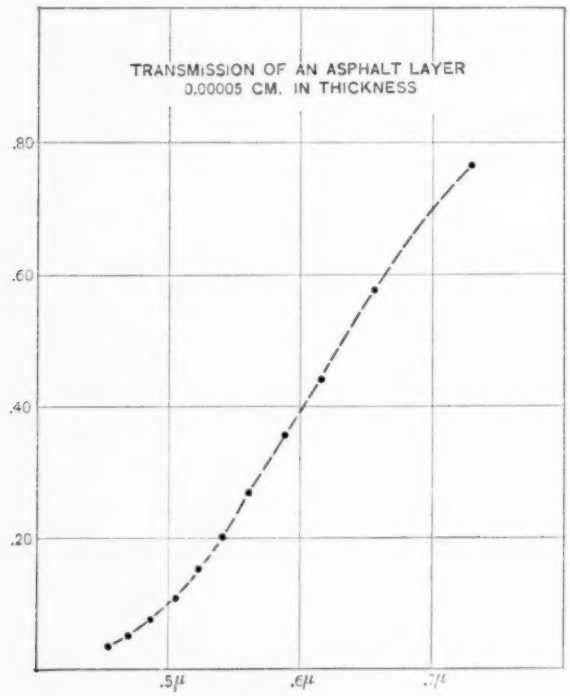


Fig. 3.

with the film of Table I. This discrepancy was due to the fact that the thickness of such films continues to diminish for a long time after they appear to be dry.

The two last mentioned films, for example, measured with the micrometer gauge about twenty-four hours after deposition, were found to be .0122 cm. and 0.0069 cm. in thickness. The next day they had fallen to 0.0026 cm. and 0.0009 cm. respectively. The

effective thickness of the former, computed from its transmitting power, in terms of that of the film of Table I., which had been measured after drying for several weeks was however only .00195 cm.

The extinction coefficients in Table I. refer to films which have been thoroughly dried and not to freshly deposited layers of asphalt varnish.

The thinner region of the double, amber-colored film near the apex of the wedge-shaped cell would have had a thickness when dry of only 0.000055 cm.

The transmission curve of this region (thickness 0.000055 cm.) is given in Fig. 3, from which it will be seen that the transparency was still diminishing at wave-length 0.45 μ. The maximum of the absorption band must therefore lie at some still shorter wave-length; perhaps in the ultra-violet.

The Anomalous Dispersion of Asphalt.

In order to determine the dispersion of asphalt for those wave-lengths for which it is transparent a prism was made by placing some fragments of solid asphaltum between two plane-parallel pieces of glass and heating carefully in a gas oven until the asphaltum began to flow, when the plates were firmly pressed together at one edge. After many trials a prism of small angle was thus obtained thin enough to transmit red, yellow and a trace of green light near its edge.

This was set up, as nearly at minimum deviation as possible in the path of the dispersed rays of a spectrometer with two prisms and the displacement of four bright lines was carefully measured.

The source of light was an electric arc plentifully supplied with lithium and sodium.

The angle o the prism was 1° 50′ 2″.

The results of these measurements are given in Table II.

Table II.

Dispersion of a prism of asphalt.

Wave-lengths.	Index of Refraction.
Li ($\lambda = 0.6708\mu$)	$n = 1.6209$
Li ($\lambda = 0.6104\mu$)	$n = 1.6282$
Na ($\lambda = 0.5896\mu$)	$n = 1.6351$
Na ($\lambda = 0.5682\mu$)	$n = 1.6339$

It will be seen that anomalous dispersion begins to manifest itself between the yellow and green. It was not possible to make measurements at shorter wave-lengths by this method on account of the opacity of the material.

MEASUREMENTS IN THE INFRA-RED.

The transmitting power of asphalt in the infra-red was studied by interposing alternately the coated portion and the uncoated portion of a strip of glass, prepared like that used in the measurements given in Table I., in the path of the rays from an acetylene flame and comparing the deflections of a Nichols radiometer exposed to the absorption spectra thus obtained with the deflections produced by the spectrum of the uninterrupted rays from the flame. The

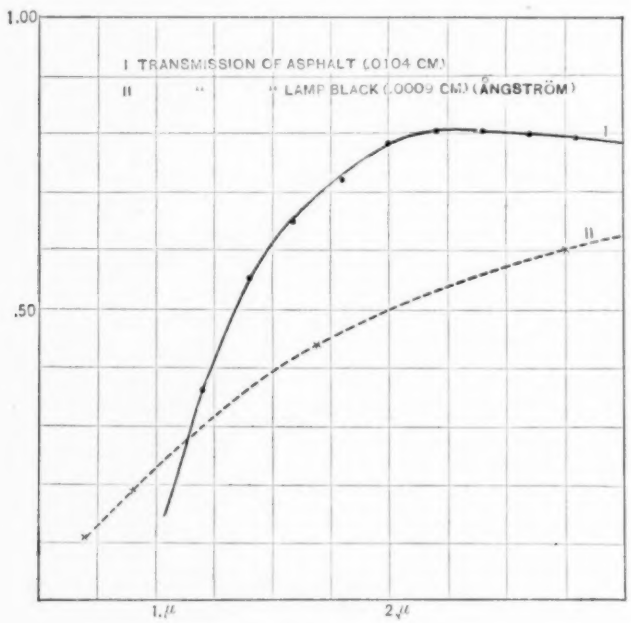


Fig. 4.

apparatus used was one employed by Mr. W. W. Coblentz in measurements of the absorption of solutions of iodine the results of which have not yet been published. It consisted of a mirror spectrometer with bisulphide prism, the radiometer being mounted in place of the eye piece so that its vanes would receive radiation of any desired

wave-length. From the observations upon the absorption in the coated and in the uncoated glass the absorption of the asphalt alone was computed. The measurements extended over the range of wave-lengths from 1.0 μ to 2.8 μ. The transmission increased rapidly from zero at 1.0 μ to about .80 at 2 μ, beyond which only slight changes in the transparency of the film were noted. There is apparently a slight maximum of transmitting power in the region 2.2 μ. Measurements could not be carried with the apparatus used beyond 2.8 μ on account of the rapidly increasing opacity of glass and carbon bisulphide, and on account of the small dispersion of the bisulphide prism for the greater wave-lengths. In order to extend the investigation to the still longer wave-lengths of the infra-red spectrum it would be necessary to repeat the measurements by means of layers of asphalt placed upon a plate of fluorite or rock salt and to make use of a prism of similar material in the spectrometer.

The results of these measurements are given in Table III. from the data contained in which the transmission curve shown in figure 4 is plotted. The thickness of the film employed was 0.010 cm. Its opacity was so complete that the disk of the sun could not be distinguished through it.

TABLE III.

Transmission of an asphalt film (0.010 *cm. in thickness*) *in the infra-red.*

Wave-length.	Transmission.	Extinction Coefficient.
1.0	.000	——
1.2	.333	104.
1.4	.550	59.8
1.6	.644	44.0
1.8	.718	33.2
2.0	.786	24.1
2.2	.809	21.2
2.4	.805	21.7
2.6	.791	23.4
2.8	.788	23.8

CONCLUSIONS.

There is much about the optical behavior of asphalt to suggest that its color may be due to the presence of carbon particles dissolved or perhaps suspended in some other medium, but the differences

between the two substances are scarcely less striking than their resemblances. We find the same transition from opacity, to transparency and this change occurs in the same region. For purposes of comparison, a portion of one of the curves given by Knut Ångström in the paper already cited has been inserted in Fig. 4. It is the transmission curve for a layer of lampblack the thickness of which was estimated at .0009 cm. in thickness. There is no significance in the comparison of a layer of asphalt with that of lampblack as regards thickness. It has been shown both by Rosicky[1] and by Stark[2] that lampblack obtained by smoking glass in the flame of a candle is of very loose structure, being equivalent to a layer of solid carbon of not more than three or four hundredths of the thickness. Ångström's values are therefore not strictly comparable with that computed for asphalt. It will be seen however that the change from opacity to transparency in the asphalt layer is much more abrupt than is the case with lampblack and that the former is more nearly transparent in those portions of the infra-red included in my measurements. A layer of lampblack .01 cm. in thickness would for example transmit only about .09 of the incident radiation of the wave-length 2 μ. Asphalt of the thickness of Ångström's layer of lampblack would on the other hand transmit .98. It has been shown by Wood[3] in a recent paper that lampblack exhibits anomalous dispersion in the visible spectrum and in this respect the two substances therefore have similar properties. The maximum of the absorption band for carbon lies in the case of some varieties of lampblack and also of layers of carbon deposited in vacuo as, for example, upon the inner surface of the bulb of incandescent lamps, in the brightest part of the visible spectrum.[4] The measurements by Rosicky and by Stark seem to indicate however that in some specimens the center of the absorption band must lie further towards the violet.

That the coloring matter in asphalt varnish consists of minute particles, possibly of carbon, which are held in suspension by the liquid may be shown by means of the following experiment:

[1] Rosicky, Wiener Berichte, 78, II., p. 407 (1878).
[2] Stark, Wiedemann's Annalen, 62, p. 351.
[3] Wood, Philosophical Magazine, 6, Vol. 1, p. 405 (1901).
[4] Nichols and Blaker, PHYSICAL REVIEW, Vol. XIII., p. 378.

If a wire ring be dipped into the varnish and withdrawn it carries with it a flat film of liquid, which is very similar to a soap film in appearance. The coloring matter in this film is not uniformly distributed, as in a solution, but tends to gather into streaks and patches as if by capillary action, and it is very speedily drawn to the boundaries of the film leaving a layer which shows only the colors of interference. Upon drying it leaves behind a nearly colorless sheet of resinous material.

THE VOWEL E.

BY LOUIS BEVIER, JR.

THE vowels *a*, as in *father*, and *a*ᵉ, as in *pat*, are quite uniform sounds in the mouths of most Americans. It is true that *a* is often sharped in New England, and that *a*ᵉ is frequently nasalized more or less, but still it is easy, by pronouncing either in the presence of a speaker from whom one desires to get a record, to secure from him a pretty accurate reproduction.

Of the subject of the present study this is not the case. In the first place *e* itself varies considerably in different combinations of actual speech, from an open *e* (*ẹ*), not differing greatly from *a*ᵉ to a close *e*, approaching the French *é* (*ẹ*). In the second place speakers are accustomed to pronounce it short in most words, as in *net*, *pet*, etc., and it is difficult to get them to prolong it in singing at a registered pitch without a noticeable alteration of its timbre, the very matter of our study. Great care, however, has been taken in this respect, that all records analyzed should sound true, when produced, and when reproduced, and the quality is, I believe, sufficiently uniform to give trustworthy results.

The vowel here to be analyzed is the open *e* (*ẹ*) of *pet*. It has not seemed necessary to attempt an examination of a still more open *e*, as for example the German *ä*, because this nuance is not normal in our speech, and because the analysis of *a*ᵉ and *ẹ* are so similar that the intermediate may be constructed theoretically with sufficient exactness. On the other hand the vowel in *pate* is not here considered because it is not a simple sound, and must be reserved until the question of diphthongs is reached.

The following table gives a sufficient number of analyses to furnish a safe basis of generalization. For full explanation of the arrangement of facts in the table the reader is referred to the discussion of the vowel *a*ᵉ, printed in the March number of this journal.

An examination of the table reveals that the upper partial, which

Analyses of the *E*-Curve.

		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII
		152	304	456	608	760	912	1064	1216	1368	1520	1672	1824	1976	2128	2280	2432	2584
1	91.0	14.1	4.4	6.6	**25.5**	4.0	3.5	5.5	6.6	2.4	4.2	5.9	**9.2**	0.4	2.0	2.9	2.6	0.2
		160	320	480	640	800	960	1120	1280	1440	1600	1760	1920	2080	2240	2400	2560	2720
1	101.8	31.6	7.9	5.7	**9.8**	2.6	3.9	**5.3**	3.9	5.7	6.7	**8.2**	1.6	1.8	2.3	1.0	1.2	0.8
6	165.8	34.3	3.7	2.3	**31.1**	1.0	0.5	2.6	0.8	4.2	**6.9**	**6.0**	2.4	1.0	1.2	1.0	0.3	0.7
		181	362	543	724	905	1086	1267	1448	1629	1810	1991	2172	2353	2534	2715	2896	3177
1	82.6	25.7	3.9	**11.1**	1.7	3.1	3.6	5.8	6.3	**8.7**	**14.1**	4.1	3.1	3.4	2.2	1.2	1.0	1.0
		192	384	576	768	960	1152	1344	1536	1728	1920	2112	2304	2496	2688	2880	3072	3264
6	57.4	4.4	5.4	**7.1**	4.9	4.9	2.3	1.2	9.4	**26.2**	**12.6**	4.0	3.6	3.1	2.6	3.1	3.3	1.9
7	47.0	12.1	7.0	**7.5**	4.3	3.6	7.9	2.1	7.0	**11.5**	**23.2**	4.9	3.6	1.5	1.3	1.1	1.0	0.4
		202	404	606	808	1010	1212	1414	1616	1818	2020	2222	2424	2626	2828	3030	3232	3434
2	64.2	24.6	2.8	**12.1**	4.1	4.7	5.9	6.2	**12.5**	**10.**	6.9	3.4	0.9	2.8	0.9	0.9	0.7	0.6
		226	452	678	904	1130	1356	1582	1808	2036	2262	2488						
1	236.0	15.7	6.9	**21.9**	3.5	6.3	7.6	17.3	**12.5**	1.5	2.6	4.2						
		256	512	768	1024	1280	1536	1792	2048	2304	2560	2816	3072	3328	3584	3840	4096	4352
1	251.6	8.8	6.6	**11.4**	**10.6**	7.8	13.6	**17.6**	6.2	4.5	7.3	5.6						
6	136.9	8.8	5.4	5.0	**14.6**	4.2	**28.8**	**18.0**	5.9	2.3	1.2	1.4	1.5	1.0	0.6	0.5	0.1	0.7
7	97.0	11.2	6.4	3.5	6.3	6.5	**17.3**	**32.3**	2.6	3.0	4.3	1.7	1.3	0.5	1.2	0.7	0.6	0.6
		272	544	816	1088	1360	1632	1904	2176	2448	2720	2992						
1	168.6	8.4	**15.8**	7.2	**14.8**	2.8	12.1	**23.7**	6.5	4.6	2.8	1.3						
1	94.4	12.3	**10.4**	**14.2**	**10.6**	7.0	**28.4**	**10.8**	3.8	1.5	1.0	0.0						

		288	576	754	1152	1440	1728	2016	2304	2592	2880	3168	3456	3744	4032	4320	4608	4896
4	**153.4**	12.3	9.4	**25.1**	7.5	8.0	**10.4**	**13.6**	5.4	1.4	1.6	0.2	1.1	0.2	0.7	1.2	0.9	1.0
		320	640	960	1280	1600	1920	2240	2560	2880	3200	3520	3840	4160	4480	4800	5120	5440
4	175.6	4.2	**34.3**	**21.0**	8.2	6.3	**11.4**	8.0	1.0	1.3	1.7	0.6	0.4	0.5	0.2	0.2	0.3	0.4
5	104.5	2.5	**13.8**	**28.8**	7.3	12.1	**14.9**	10.0	1.9	1.1	1.4	0.9	1.8	0.5	0.2	0.1	2.1	0.6
7	231.5	4.5	**37.8**	6.0	6.4	14.4	**25.9**	1.4	3.6									
8	**68.1**	20.0	**28.2**	**10.6**	6.8	4.1	**18.2**	5.4	0.6	0.9	0.7	0.9	1.3	0.9	0.2	0.4	0.3	0.5
9	**39.4**	15.2	**30.0**	9.9	3.3	6.9	**19.8**	2.5	3.5	1.3	2.0	1.3	0.5	0.5	0.8	0.5	0.5	1.5
		341	682	1023	1364	1705	2046	2387	2738	3079	3410	3751	4092	4433	4774	5115	5476	5817
4	194.7	7.0	**15.9**	**23.1**	7.0	7.4	**12.4**	4.6	5.9	3.8	2.9	2.5	1.9	2.0	1.6	0.2	0.7	1.1
		384	768	1152	1536	1920	2304	2688	3072	3456	3840	4224	4608	4992	5376	5760	6144	6528
4	**79.3**	9.6	**25.0**	11.8	12.4	**16.8**	7.4	7.3	1.4	0.9	1.4	0.7	1.3	0.9	1.0	0.6	0.6	0.9
5	148.8	2.2	9.6	**30.3**	15.9	**18.2**	10.5	9.1	4.2									
8	61.9	11.8	**19.7**	3.9	21.8	**26.7**	5.3	0.5	1.8	1.9	1.1	0.6	1.3	0.8	0.7	0.6	1.3	0.2
9	113.3	10.8	**19.6**	**14.7**	14.3	**30.0**	1.0	1.9	2.6	0.5	0.7	0.6	0.4	0.4	1.0	0.1	0.7	0.8
		480	960	1440	1920	2400	2880	3360	3840									
4	278.8	9.0	**40.6**	**21.7**	**13.8**	6.4	2.5	5.6	0.4									
		512	1024	1536	2048	2560	3072	3584	4096	4608	5120	5632	6144	6656	7168	7680	8192	8704
5	229.2	5.5	**27.0**	**30.2**	**24.3**	8.4	0.4	3.0	1.2									
7	340.0	4.5	**13.9**	**37.5**	**29.0**	3.8	6.2	3.3	1.8									
9	47.4	19.3	**25.7**	**26.6**	**10.1**	3.4	1.7	1.3	1.3	1.5	1.1	1.3	1.7	1.0	0.8	0.8	1.2	1.2
		640	1280	1920	2560	3200	3840	4180	5120									
10	107.4	**63.8**	8.9	**21.5**	2.7	1.5	0.6	0.3	0.7									

is most characteristic for e, and always present, lies higher in the musical scale than for a^e by an interval somewhat greater than a whole tone. The frequency of this characteristic and strongly reinforced upper partial is in the neighborhood of 1,800, whereas that of a^e lay as we saw (l. c.) at about 1,550 $\left(\frac{1,550}{1,800} < \frac{8}{9}\right)$. The actual frequency of this important upper partial varies within not very narrow limits, according to individual differences of utterance, and acccording to the pitch of the fundamental of which it must be an exact multiple. Thus in the table we find on I. 152, 1,824 (XII.) with an amplitude percentage of 9.2; on I. 160, 1,760 (XI.) with 8.2 and 6.0 respectively in the two examples; on I. 181, 1,810 (X.) with 14.1, and so on to the highest tones analyzed.

This region of resonance extends over a considerable range, so that on low fundamentals two consecutive upper partials may be strongly reinforced. For example, I. 192 of voice 6 shows both IX. and X. (1,728 and 1,920) strong, and so in many other examples. The limits may be approximately set at 1,600 and 1,950 with the maximum generally at about 1,800.

Besides this resonance there is always present at least one other, and often two others of lower pitch. These coincide very closely with those described in the study of a^e save that the lower centers at about 620 (cf. 650 for a^e). The upper has a frequency of about 1,050 as for a^e. A good example in the table which shows both of these resonances, in addition to the principal one above described, may be seen in I. 272 of voice 1. Here II. (544) is strong (15.8), IV. (1,088) is also strong (14.8), and VII. (1,904) predominatingly strong with an amplitude percentage of 23.7 The real strength of the last may be best appreciated if the same record is computed in energy percentages, which would give the following results: I. 0.2; II. 2.3; III. 1.1, IV. 8.0; V. 0.5; VI. 12.1; VII. 63.3; VIII. 6.2; IX. 3.9; X. 1.8; XI. 0.5.

More frequently the analysis shows but one of the two lower resonances at all important, either that in the neighborhood of 620 or a compromise between the two. The essential point for the character of the vowel is that there shall be, in addition to the uppermost resonance, a certain fullness of resonance at one or more

lower points. This can best be made plain by a detailed examination of several concrete cases. Take for example the two specimens at 160 by voices 1 and 6. Each shows the characteristic high resonance at XI. (1,760). This is a little below the point I have designated as the normal maximum, but is nearer to it than the next upper partial (1,920) would be. Still many examples may be found where 1,920 would be the dominant upper partial, representing presumably, other things being equal, a slightly closer *e*. Following the records down the scale toward the fundamental, X., IX. and VIII. are weak, as they should be; VII. shows in each a greater amplitude percentage, but not quite as much greater as we should usually find at that pitch (1,120) which is quite near a region of resonance. Again VI. and V. are weak, which is according to the rule, and IV. is strong. In the second case it is very strong, much more so than is usual.

Compare next the five examples by different voices on the fundamental 320. Here II., which falls near the lowest resonance maximum, is strong in all, varying from the high amplitude percentage 37.8 to the moderate 13.8. On the other hand III. falls a little too low for strong reinforcement in most normal utterances. Still the first and second examples show considerable reinforcement, particularly the second where III. is very strong, At IV. all are relatively weak, as they should be. At V. the resonance begins to be important again in the case of the second and third examples, but not in the others. VI. falls near the resonance maximum and is consequently strong in all. Even VII. in the first and second examples is quite strong, although considerably above the usual *e* resonance.

From a careful study of the table, and from numerous other analyses, the definition of *e* may be formulated as follows: The vowel *e* is a composite sound containing: (1) The chord-tone, or fundamental, varying within wide limits of loudness. In general it is strong below 200, but not so strong as that of *a*. From 200 to 600 it is weak, but not so weak as that of *a*. Above 600 it falls within a region of strong resonance and is very strongly reinforced.

(2) A characteristic *e* resonance in the region of 1,800. This

resonance is always present, and is most important, but its pitch varies within moderate limits, as explained.

(3) A strong resonance at one or two lower points, centering at about 620 and 1,050 respectively. Both may be present, but at least one of them must be.

As was done for *a'*, these facts may perhaps be best shown by plotting a resonance curve of amplitude percentages, obtained by averaging all the analyses made. This curve shows the women's

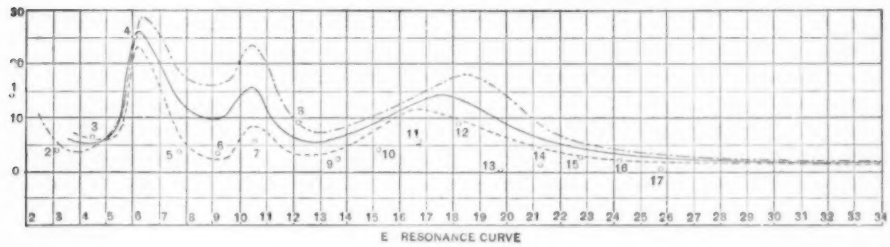


Fig. 1.

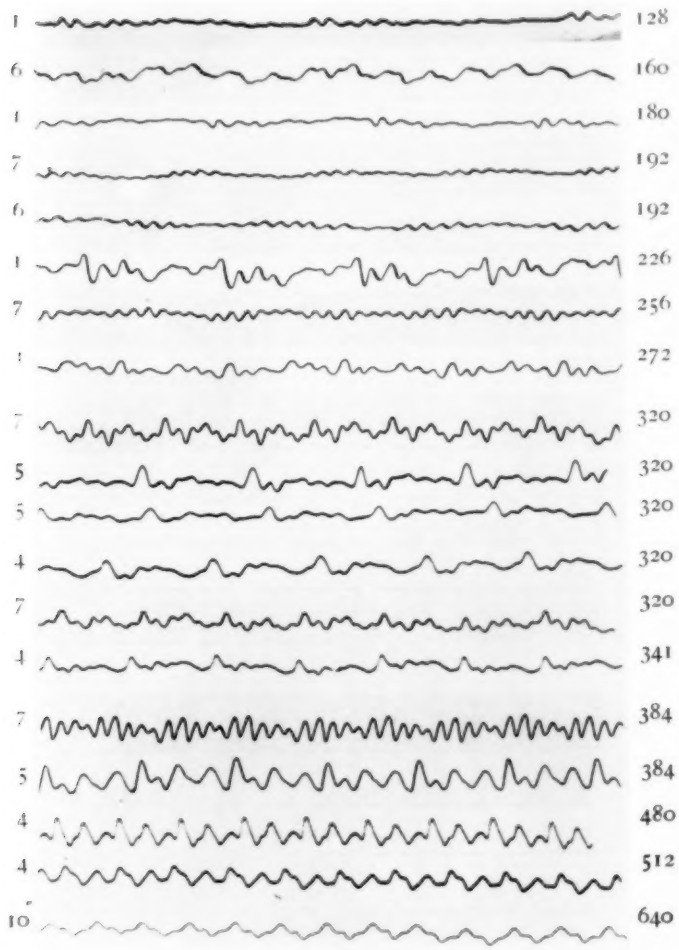
line, the men's line, and the average of both as for *a'*. We observe that the resonance begins to rise very rapidly at about 550, reaches a very pronounced maximum at about 620, descends thence and rises to its second maximum at 1,050. From this point it descends abruptly, to rise gradually once more and reach its final maximum at about 1,800. Here a noteworthy difference appears between the women's line, and that of the men's voices, the latter showing the maximum on the average at about 1,700 and the former at about 1,850. This is true as an average result, but many records of men's voices show the resonance maximum as high as 1,900, and *vice versa*, many individual examples of women's voices as low as 1,700. There does, however, seem to be a tendency on higher fundamentals, both of men's and women's voices, to pitch this resonance a little higher.

As before, (l. c.), an individual record is plotted for the sake of illustration. It follows the average very closely. The fundamental is 152. I. (152), IV. (608), VII. (1,064), VIII. (1,216), XI. (1,672), and XII. (1,824) are important, and the rest weak. The maxima are in this case at IV., VIII. and XII. respectively.

For comparison a sheet of *e*-curves is added. The most casual

inspection will show that the characteristic resonance is of higher pitch than for a'. A simple count of the minor crests is the most obvious test. Thus at 320 these minor crests number six, giving a frequency of 1,920; at 384 five, again 1,920; at 256 seven, giving a frequency of 1,792, etc.

It may be interesting to compare two similar records lying an octave apart in fundamental pitch. The comparison will be most striking in the case of 320 by voice 7, and 640 by voice 10, the former a contralto, the latter a soprano. The record on 320 is essentially a succession of triplets, two to each fundamental wave, while that on 640 is a succession of simple triplets. The elements 640 and 1,920 are common to both, and hence their great similarity; but in the 320-record V. (1,600) is also present, and makes the one triplet different from its fellow. The fundamental at 320 is too weak to count so far as the unassisted eye can discern. These curves have for convenience of publication been reduced to one-third of their size as recorded by the transcribing instrument.


1
128
6
160
1
180
7
192
6
192
1
226
7
256
1
272
7
320
5
320
5
320
4
320
7
320
4
341
7
384
5
384
4
480
4
512
10
640

E — Curves

THE VELOCITY OF IONS FROM HOT PLATINUM WIRES. PART I.

By C. D. Child.

MANY investigations have been made on the discharge from hot wires, but none on the velocity of the ions carrying this discharge. As far as the writer is aware no quantitative measurements of any kind have been taken. The fact that the discharge from a positive platinum wire is greater than from a negative one led the writer to suspect that the positive ions move more rapidly than the negative ones, and for this reason, if for no other, the subject seemed worthy of study. Since this investigation was commenced an article has been published by Rutherford[1] concerning the velocity of ions from a hot platinum foil. His article covers some of the ground which is included in this. The methods used were not, however, identical and the objects in mind were different, so that this investigation confirms his, but does not to any great extent duplicate it.

Irregularities in the Rate of Discharge.—The writer imagined before beginning the work that the discharge from a hot platinum wire through which a constant current is flowing would be constant. Examination showed that it would be much nearer the truth to say that the discharge is never constant. The investigation proved to be little more than an attempt to find the different causes for the variations.

The wire used was heated by passing through it an electric current produced by a storage battery. Resistance was placed in series with the wire and the potential was varied by varying the position of a ground connection on this resistance. A shunt was placed about the hot wire and a point midway on this shunt was assumed to have the same potential as the wire. The potential

[1] Phys. Rev., 13, 321.

difference between this point and the ground was measured by a voltmeter.

The outer cyclinder was connected to the electrometer and also to the ground. In making an observation of the discharge the connection to the ground was first broken and after a given length of time the electrometer was disconnected from the cylinder. The deflection of the electrometer would then show the amount of discharge which had passed to the cylinder.

There was one cause of difficulty which must be ascribed to lack of care in making observations. The current through the wires was produced by a storage battery. It was assumed that the electromotive force of the battery was constant. It happened, however, that it was slightly variable. It also happened that at certain temperatures very slight changes in the temperature of the wire produced large changes in the rate of discharge and the first observations were made at just these temperatures. As a result the varying changes of current through the wire made large changes in the rate of discharge. Later, of course, proper care was taken to keep the current constant.

Rate of Discharge at first Decreases.—It was found that in general the discharge from the wire was at first large, decreasing for a short time rapidly, and then increasing slowly. The following are the data taken in one case when the wire was heated for the first time. The length of the wire was 6.5 cm., the diameter was .3 mm., the diameter of the surrounding cylinder was 48 cm., its width 6 cm. The current through the wire was 3.8 ampères. This was sufficient to heat the wire to a dull red. The potential difference between the wire and the cylinder was 35 volts, the wire being charged positively. In such a case the discharge is carried by positive ions and will be called the positive discharge. This is contrary to the usage which some have adopted, but in the light of the facts to be described later it seems best to use this terminology. The discharge carried by the negative ions will be called the negative discharge. Column 1 gives the time of the observation after the current was commenced. Column 2 gives the deflection which took place in four seconds. There was a deflection of 1.9 scale divisions per volt. The capacity of the electrometer and of a small condenser placed in multiple with it was 4.43×10^{-3} micro-farads.

TABLE I.

Time.		Deflection of Electrometer.
Minutes.	Seconds.	
	10	8.3
1	30	6.2
3		5.1
5		3
6		3

It seems probable that this large discharge at the beginning was caused by impurities of some sort in the wire which were soon burnt out, or possibly by gases that had been absorbed by the platinum. The wire here used was weighed just before the observations were made and again afterwards. If there was any loss in the weight, it must have been less than .1 mg. But the fact that there was no appreciable loss of weight proves nothing, since the extra amount of discharge could be carried by an amount of matter far too small to be detected by weighing.

The decrease in the rate of discharge when the wire was first heated was very irregular, and in some cases it was scarcely noticeable. This decrease was more noticeable when the temperature was not very high.

This decrease was followed by an increase, and this increase was much more noticeable when the wire was white hot. In one case a current of 5.5 ampères was passed through a wire .3 mm. in diameter for 20 minutes and the rate of discharge increased during that time at least 50 per cent. When this increase was first observed it was thought that it might perhaps be due to an increase in the température of the wire occasioned by an increase in its resistance. On investigating the matter it was found that the resistance did indeed increase on account of a slight lengthening of the wire, and on account of a decrease in weight. The increase in length was, no doubt, due to a small tension that was put upon the wire to keep it straight.

However, it was afterwards found that raising the temperature did not cause an increase in the rate of discharge and other causes producing large changes in the discharge were found. The data

that were taken of the increase in length and decrease in weight have, therefore, no bearing on the matter in hand.

The real cause of the increase in the discharge can be much better considered after other experiments have been described. The discussion of this will, therefore, be postponed for the present.

This continual change in the rate of discharge made it impossible to secure accurate data in much of the work, but by allowing the current to flow through the wire for a short time before making observations it was possible to have the discharge nearly constant and to secure data approximating the truth.

Dependence of the Rate of Discharge on the Current flowing through the Wire.—As has already been stated the rate of discharge at certain temperatures of the wire was largely influenced by small changes in the current flowing through the wire. Table II. shows this dependence. Column 1 gives the current flowing through the wire. Column 2 gives the rate of discharge in ampères with positive discharge, column 3 those with the negative. The potential difference between the wire and surrounding cylinder was 40 volts. The diameter of the cylinder was 4.8 cm. and its length 6 cm.

Table II.

Current Through Wire.	Positive Discharge.	Current Through Wire.	Positive Discharge.	Negative Discharge.
3.5	$.13\times10^{-9}$	5.5	3.4×10^{-9}	$.13\times10^{-9}$
3.7	.25 "	5.7	3.3 "	.38 "
4.	3. "	6.	3.3 "	2.5 "
4.2	3.5 "	6.3	3.5 "	2.4 "
4.5	4. "	6.5	3.4 "	2.8 "
5.	4. "	6.8	3.3 "	2.5 "

The observations were not carried further, because with larger currents the wire melted. In no case was the negative discharge found to be as large as the positive, although these observations were taken many times.

The positive discharge passes through a maximum. Rutherford states that the discharge from a hot platinum sheet in like manner passes through a maximum. The observations regarding the rate of discharge from a wire were made before Rutherford's article was published, so that the reality of this decrease is fully established.

In explanation of the discharge the following may be said. When the temperature is barely sufficient to produce a few ions the amount of discharge is limited by the number of ions present. The number, no doubt, increases rapidly as higher temperatures are produced, but the discharge is soon checked by the effect of the ions on the field about the wire. The charges on the ions change the potential about the wire, until the potential gradient at the wire becomes very small and no more ions are then drawn out than are sufficient to keep the field in this condition. When this occurs the rate of discharge is not limited by the number of ions, but by the rapidity with which the ions move out of the field. If under these conditions the average velocity of the ions should decrease, the rate of discharge from the wire would decrease.

Rutherford explains the decrease in the rate of discharge observed at higher temperatures by supposing that at those temperatures ions begin to be sent off differing from those which had previously carried the discharge and that those ions move more slowly. Other facts bearing on this explanation will be given later.

Rutherford has investigated fully the position of the maximum rate of discharge under different conditions. The facts observed by myself were in harmony with those recorded by him, but no very extended investigation was made concerning the matter.

It is to be noticed that the negative discharge begins at nearly the same temperatures as that at which the positive decreases. This will be considered in connection with other facts.

Dependence of Discharge on Potential Difference.—The variation of the rate of discharge with the variation of the potential difference is shown in Table III. Column 1 gives the potential difference between the wire and the cylinder, column 2 the positive discharge; column 3 the negative. The current through the wire was 6.2 ampères. The other conditions were the same as those in Table II.

TABLE III.

Potential Difference.	Positive Discharge.	Negative Discharge.
46	4.5×10^{-9}	3.5×10^{-9}
30	2.1 "	1.4 "
22	1.2 "	.65 "
11	.2 "	.1 "

Velocity of Ions.—Having thus investigated some of the peculiarities of the discharge from a hot wire, the investigation of the velocity of the ions carrying this discharge was undertaken. Four different methods were employed. In general those who have studied the ionization of gases have found that the negative ions move more rapidly than the positive. The only exception to this rule which has heretofore been found was in the case of discharge produced by the electric arc. The present case, however, presents another exception. It, therefore, seemed well to have as positive a proof as was possible that this was an exception. Moreover the different methods brought out several facts of considerable interest.

These methods have all been used in the examination of ions produced by the electric arc, and were described in that work.[1]

First Method.—In the first method the only necessary measurements were those of the rate of discharge from the wire to the cylinder and of the potential gradient between these.

When discharge is carried by ions of one sign only which pass from an inner to an outer cylinder,

$$\frac{dV}{dr} = -\sqrt{\frac{4\pi I_1}{K_1} + \frac{C^2}{r^2}},$$

where V is the value of the potential at any point, k_1 is the velocity of the positive ions for unit potential gradient, r the distance from the center of the cylinder, I_1 the current through unit area at a unit's distance from the center and C a constant of integration. If there is a very large source of ions at the surface of the inner cylinder, $C = -r_0^2$ where r_0 is the radius of the inner cylinder and the equation becomes

$$\frac{dV}{dr} = -\sqrt{\frac{4\pi I_1}{K}\left(1 - \frac{r_0^2}{r^2}\right)}.$$

When a small platinum wire is used as the inner cylinder the term $\frac{r_0^2}{r^2}$ may be omitted and we have

$$\frac{dV}{dr} = -\sqrt{\frac{4\pi I_1}{K_1}},$$

and

[1] PHYS. REV., 14, 65.

$$V = -\sqrt{\frac{4\pi I_1}{K_1}}\, r,$$

if we assume zero potential at the wire, or

$$V_b = \sqrt{\frac{4\pi I_1}{K_1}}\, b,$$

where b is the radius of the outer cylinder and V_b is the potential difference between that and the wire.

If we are dealing with discharge produced by ions having different velocities we may substitute K_1 for k_1 where

$$K_1 = \frac{\Sigma\, k_1 n_1 e_1}{\Sigma\, n_1 e_1},$$

n_1 being the number of ions per unit volume which have the velocity k_1 and e_1 the charge which each one of these have, the summation being extended to all the positive ions. This K_1 we may call the average velocity of the positive ions.

Potential About the Wire.—The potential was found by a water dropper, the same that has already been described.[1] The wire was .3 mm. in diameter, the same size which has been used in the preceding experiment. A current of 6.3 ampères was passed through the wires. A cylinder 20 cm. in diameter was placed about the wire. The potential at different points is shown in Table IV. The first column gives the distance from the center of the cylinder, and the second the potential difference between the center of the cylinder and the point considered.

TABLE IV.

No. of cms. from Center.	Pd. Between Wire and Point.
1	10
2	20
3	29.5
4	41
5	51
6	59
8	78

The potential was found to fluctuate somewhat, due no doubt to the convection currents about the wire. These variations amounted

[1] PHYS. REV., 12, 68.

to about one volt on either side of the potential which was recorded. The recorded readings were, therefore, liable to an error of about one volt. This table was at first taken when positive discharge was passing from the wire, but it was practically the same when the discharge was negative. Thus it was found that if a ground on the shunt placed between the wire and the cylinder was shifted until the water dropper was at zero potential, the water dropper would remain at very nearly the same potential when the potentials of wire and cylinder were reversed. The variations caused by reversing the discharge were no greater than the continual fluctuations. A test was made in this way at each of the points given in Table VI., and the above statement was found to hold for each. These data, therefore, as truly represent the potential gradient in the case of negative discharge as in that of positive.

The potential is practically proportional to the distance from the center, showing that we have a right to say that

$$V = \frac{4\pi I_1}{K_1} r$$

and consequently

$$K_1 = \frac{4\pi I_1 b^2}{V_b}$$

In other words the current is directly proportional to the average velocity of the ions.

Ions Produced at or Near the Wire.—This shows conclusively that the ions are produced at or very near the surface of the wire. If they were produced at the surface of the cylinder surrounding the wire or between the wire and the cylinder, there would be an entirely different potential gradient from that which actually exists. That which exists could only be caused by ions starting from the wire.

Positive Ions Move the More Rapidly.—No further proof than this is needed to show that the average velocity of the positive ions is greater than that of the negative, since it has already been shown that the positive discharge at these temperatures of the wire is greater than the negative. This follows immediately from the formula

$$K_1 = \frac{4\pi I_1 b^2}{V_b^2}.$$

The potential between the wire and a cylinder 12 cm. in diameter was examined and again the potential difference between the point examined and the wire was found to be practically proportional to the distance from the wire, whether the charge was positive or negative. Other cylinders with different diameters were tried with the same result.

Rate of Discharge to Cylinders of Different Diameters.—The values of I_1 for a few different cylinders were then found. Very similar work to this has already been done by Rutherford, so that only a few observations were taken. In finding I_1 the outer cylinder was connected to an electrometer and the change of potential taking place in a given length of time was noted. The exact method of doing this has already been described.[1] From this change of potential the total current flowing to the cylinder could be found by dividing the change of potential of the electrometer by the time, here 8 seconds, and multiplying by the capacity of the electrometer. The electrometer was the same as that already used, and its capacity was 4.43×10^{-3} microfarads. From the total current I_1 is found by dividing by 2π times the width of the cylinder and from this K_1 may be computed by the use of the formula.

The results of this work are given in Table V. Column 1 gives the radius of the cylinder, column 2 the total positive current flowing to the surrounding cylinder, column 3 the total negative current, column 4 the computed velocity of the positive ions, column 5 the velocity of the negative ions. The potential difference between the wire and cylinder was 40 volts. The length of each of the cylinders was 6 cm., and the length of the hot wire was also 6 cm. The current through the wire 6.3 ampères.

TABLE V.

Radius of Cylinder.	Positive Discharge.	Negative Discharge.	K_1	K_2
2.4	3.5×10^{-9}	2.4×10^{-9}	3.8	2.6
6	.43 "	.30 "	2.4	1.7
10	.13 "	.10 "	1.95	1.5

These values for K_1 agree well with those found by Rutherford.

[1] PHYS. REV., 12, 74.

It will be noticed that the values for K_1 and K_2 decrease as the distance from the source of ionization increases. This agrees with what has already been found in the case of discharge from flames and from the electric arc and with what Rutherford has found from a hot platinum foil.

The variation of the rate of discharge with the different potential differences has already been studied in one case. According to the theory the rates of discharge should vary as the square of the potential differences. In reality it increases more rapidly than this, showing that at higher potential differences the velocity of the ions is greater than at lower. This again agrees with what has already been found in other cases. All of these facts are in agreement with the general statement that the longer the time that the ions have been in existence, the more slowly they move.

Velocity of the Ions, Second Method.—A second method used to find the velocity of the ions was a modification of one employed by Zeleny [1] to find the velocity of ions produced by X-rays.

First Modification of Zeleny's Mehod.—Practically the same modifications of Zeleny's method were necessary here as were necessary in the investigation of the electric arc.[2] In the case studied by him a lamina of gas perpendicular to the axis of the cylinders was ionized. In the case here studied a portion of the gas along the length of the inner cylinder was ionized. Consequently his method must be somewhat modified and this may be done in either of two ways. In the first let AB, Fig. 1, be the hot wire, the wires at each of its extremities having such conductivity as to remain comparatively cool. This wire is surrounded by two cylinders, CC' and DD', placed concentrically with the wire and insulated from each other at LL'. A blast of air is blown in the direction of the arrow.

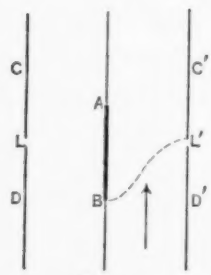


Fig. 1.

When the potential difference between the wire and the outer cylinder is small, no discharge will go to DD', but it will be blown to the upper cylinder, the ions from B moving in some such line as

[1] Phil. Trans. of Roy. Soc., 195, 193.
[2] PHYS. REV., 14, 66.

indicated by the dotted line in the diagram. As the potential difference is increased, the discharge will move more directly across to the lower cylinder. If the velocity of the ions is great per unit potential gradient, the discharge will begin to pass to the lower cylinder with smaller potential differences than it will, if the velocity of the ions is small. In this way the velocities of the positive and negative ions can be compared.

As has been already pointed out[2] this method shows the velocity of the most rapidly moving ions. There is reason to suppose that, at least in the positive discharge, there are different kinds of ions aiding in the discharge. This will be explained more in detail shortly. If this be so, this particular arrangement will give no information concerning the slower ones. They will at all times be carried to CC'.

An exact determination of the velocity is not possible by this method because the field between B and DD' cannot be mathematically discussed. Furthermore, the point B could not be determined with accuracy. B is supposed to be the point where the hot wire ends and the cold one begins, but manifestly the heat from the hot wire will be conducted off by the cold one, so that no abrupt change in temperature occurs at the point where the two unite. But though the field is thus irregular and the point B somewhat indeterminate, it is still true that the greater the velocity of the ions, the smaller the potential difference necessary to cause them to pass to DD'.

In making observations one might either keep the potential difference between the wire and the outer cylinder constant, and move AB one way or the other, until the discharge ceases to pass to DD', or one could leave AB fixed and change the potential difference. This latter procedure is the simpler in practice.

It is not possible, however, to determine absolutely the potential at which the discharge begins to pass to the lower cylinder. As may be seen in Table VI., a very small discharge passes to DD' even with small potential differences. As the potential difference is increased this discharge does not at first increase rapidly, but at length a potential is found at which it does. This may be taken as the potential at which the discharge begins. The discharge with

[2] PHYS. REV., 14, 67.

smaller potential differences may be due to irregularities of the field, or possibly a very few of the ions have a greater velocity than the others.

In making observations it is necessary to note the rate with several potential differences, to plot a curve with the data thus taken, and to determine the potential from this curve at which the discharge may be said to begin.

Such data are given in the following tables. The gasometer used and the arrangement of the apparatus was, as far as possible, the same as that previously described.[1] In all of the following data the inner wire was .3 mm. in diameter, the outer cylinder 4 cm. in diameter.

With the data given in Table VI. the velocity of the air blast was 23.7 cm. per second. The point B was approximately 1.7 cm. below ee'. Column 1 gives the potential difference between the wire and the outer cylinder, columns 2 and 3 give the corresponding deflections of the electrometer for the positive and negative discharges. The current passing through the wire was 6.2 ampères.

TABLE VI.

Potential Difference.	Rate of + Discharge.	Rate of — Discharge.
48.4	8.5	3.
35.2	5.2	.4
20.9	.7	.2
17.6	.2	.1
9.9	.1	.1

These data are plotted in Fig. 2, lines 1 and 2. From the diagram we see that we may consider the positive discharge to begin at 18 volts, the negative at 33 volts.

A set of observations were then made with B 3 cm. below ee'. This set is given in Table VII.

TABLE VII.

Potential Difference.	Rate of + Discharge.	Rate of — Discharge.
45	20.4	6.3
33	10.4	3.7
19	3.1	.4
14	.8	.1
11	.1	—

[1] PHYS. REV., 14, 69.

These data are plotted in Fig. 2, lines 3 and 4. Here we may consider the positive discharge to begin at 12 volts and the negative at 18.

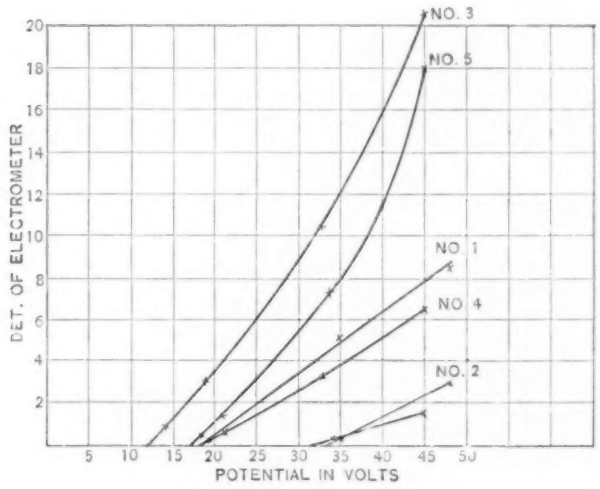


Fig. 2.

Observations were then taken with the same conditions as in the preceding set except that the air blown between the cylinders has twice the velocity that it had in the other experiments. The observations are given in Table VIII.

TABLE VIII.

Potential Difference.	Rate of + Discharge.	Rate of − Discharge.
45	18.4	1.6
34	17.5	.4
21	1.5	.1
18	.3	
11		

These data are plotted in Fig. 2, lines 5 and 6. We may here consider the positive discharge to begin at 17 volts and the negative at 30.5. In all of these cases the data indicate that the more rapidly moving ions of the positive discharge have a greater velocity than such ions of the negative discharge.

Third Method of Comparing the Velocities.—The arrangement for a second modification of Zeleny's method is indicated in Fig. 3.

This is the same as the preceding except that the hot wire AB is placed entirely below LL'. In this case the discharge would all pass to DD', if the air were stationary and if the field were not modified by the presence of ions. When the air is blown past AB some of the discharge will be carried to CC', provided the potential difference between the wire and the cylinder is not large. If it is large, the ions should all be drawn to DD' before the air could drive any of them past DD'. The more rapidly the ions move for the same potential gradient, the smaller will be the potential difference necessary to keep the ions from passing to DD'.

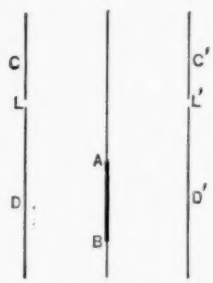


Fig. 3.

As has been previously pointed out, if there are ions present having different velocities, this method does not give us information concerning the average velocity of the ions, but concerning the velocity of the slowest moving ones.

If CC' be connected to an electrometer, and the potential difference between the wire and the cylinder be increased from zero, the electrometer would be expected to show at first a discharge passing to CC'. This should afterwards decrease and finally cease. This at least would be what we should expect if no account were taken of the modification of the field due to the ions drawn out from the wire. But as has already been shown the presence of the ions distorts the field, so that the lines of force are no longer perpendicular to the axis, but run from A up to CC'. Furthermore the field may be changed materially by the ions carried by the convection currents.

In spite of these difficulties the investigation disclosed a most interesting fact. It was found that when the wire was hot enough to produce positive discharge, but not hot enough to produce negative, the positive discharge increased at first as the potential difference was increased, and then decreased, soon ceasing altogether, but when the wire was hot enough to allow either positive or negative discharge, the rate of discharge increased continuously with increasing potential difference. That is, at lower temperatures the ions behaved very much as they did in the case studied by Zeleny, but at higher temperatures, they behaved in an entirely different manner.

In order to find the conditions under which this difference in temperature began, several sets of observations were taken with different amounts of current flowing through the wire. These are given in Table IX. The discharge here is positive in each case. The velocity of the air was 5.5 cm. per second. The distance from A to the plane cc' was 4.5 cm.

TABLE IX.

Potential Difference.	Deflection of Needle.	Potential Difference.	Deflection of Needle.	Potential Difference.	Deflection of Needle.
Current = 4.5 Ampères.		Current = 5.5 Ampères.		Current = 6.2 Ampères.	
7	1.3	7	2.9	9	3.2
10	1.8	12	3.9	14	5.9
14	1.0	20	2.6	25	8.4
17	.6	24	1.8	37	11.4
22	.2	31.5	.4	45	18.4
		34	.2		
Current = 5 Ampères.		Current = 6 Ampères.		Current = 6.5 Ampères.	
7	2.8	6	2.4	9	3.3
11.5	3	10	3.9	18.5	8.5
16	2	16	5.4	27	10.9
22	1	25	4.4	37	15.4
27	.3	37	2.4	45	22
		45	1.3		

The data of these curves are plotted in Fig. 4.

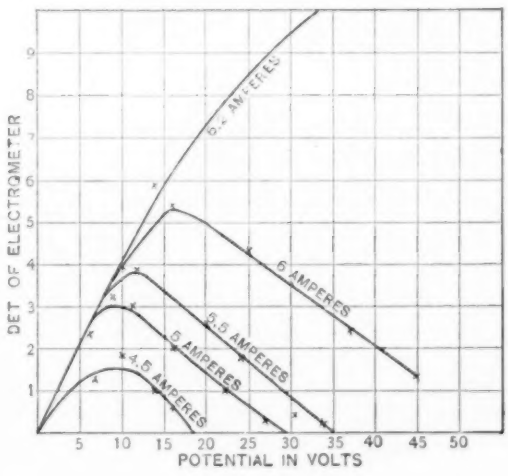


Fig. 4.

Possible Cause for Peculiarities of these Data.—There are three causes which could conceivably have produced the effect here observed. There might be more ions about the field as the wire becomes hotter and consequently greater distortion of the field; the convection currents might become stronger and more ions be carried up by them; or some of the ions might move more slowly at the higher temperatures and occasion a smaller rate of discharge.

The first explanation does not seem reasonable, for in all probability the space about the wire contains at all of these temperatures the same amount of electricity. By referring to Table II. we see that the rate of discharge from the wire ceases to increase when the amount of current passing through the wire was over 4.5 ampères. With any greater current than this the field appears to contain as many ions as was possible. But in the observations the current through the wire was at least 4.5 ampères.

Possibility of Error Due to Convection Currents.—In order to examine further the action of the convection currents, the apparatus was turned the other side up, the air from the gasometer being forced downward from above. The discharge seemed to show even less tendency to decrease with higher potential differences. This does not prove that the convection currents have no effect, since even with this condition of the apparatus the convection currents would mix the air somewhat and it might easily be that the slowly moving ions would be affected more by such currents than by the electric field. But when one considers the fact that reversing the direction of the convection currents does not change the result, that there is no reason to suppose that there is any great change in these currents at this temperature and that we have other reasons for thinking that there is a decided change in the condition of the ionization at this temperature, it seems most reasonable to explain these curves by saying that at these higher temperatures at least some ions move much more slowly than those produced at lower temperatures.

Discharge at Higher Potentials.—The distance from A to ee' was increased to 10 cm. But there was no decrease in the rate of discharge at higher potentials as compared with those of lower potentials. Still higher potentials were then used. In order to do this with the means at my command it was necessary to keep the wire

at zero potential and to change the potential of the outer cylinder by means of a water battery. This is the same method as that which has been used in studying the discharge from the electric arc.[1] Observations were taken up to 150 volts. These are given in Table X. Both the positive and negative discharges were noted. The current through the wire was 6.3 ampères. Column 1 gives the potential difference between AB and DD'. Column 2 the positive discharge and column 3 the negative.

TABLE X.

Potential Difference.	Positive Deflection.	Negative Deflection.
40	2.4	2.0
70	3.4	3.0
100	5.0	3.6
150	7.0	3.2

There is here no tendency for the rate of discharge to become smaller at the higher potentials. But the negative discharge shows more indication of decreasing than the positive. This is not in any way inconsistent with what has already been found. We have heretofore been comparing the average velocities of the positive and the negative ions or the velocities of the most rapidly moving ions. Here the velocities of those which move the least rapidly are compared, and apparently the positive discharge contains ions moving more slowly than any of the negative. It may well be that with the more rapidly moving ions of the positive discharge there are also a few very slowly moving ones. If there were but few of these they would have but little effect on the average velocities which were found by the first method and would not show at all in the second method.

Ions Produced Without a Field.—However, the fact that it was so difficult to get rid of these ions by drawing them out in a strong field suggested that we were not dealing with ions but with some sort of "emanation." The first attempt to test this was made by keeping the cylinder DD', Fig. 3, at the same potential as the wire and testing the condition of the air blown into CC'. It was thought

[1] PHYS. REV., 14, 70.

at first that any emanation would thus be blown into CC', but that no ions would leave the wire, if there was no field about it. It was found that as soon as sufficient current was sent through the wire to bring it to a temperature at which the positive ions could be produced, the air blown into the upper cylinder from about the wire allowed a discharge to pass through it. Table XI. gives the data taken in this case. Column 1 gives the current through the wire in ampères, column 2 the deflection of the electrometer produced by the positive discharge to CC', column 3 that produced by the negative. Through this series of readings the cylinder was kept at the potential of the wire. The distance from A to ee' was 4 cm. The velocity of the air was 24 cm. per second.

TABLE XI.

Current Through the Wire.	+ Discharge to CC'.	− Discharge to CC'.
5.4	.0	.0
5.8	.8	.8
6.2	2.5	2.3
6.5	3.	3.

The positive and negative discharges were practically the same.

Further thought, however, showed that this was not a proof that there was an emanation sent out from the wires, for if the air about the wire was ionized to more than molecular distances, these ions might be carried by convection currents away from the wire and, mingling with the air, be carried into cylinder CC'. This would account for the discharge which has been noted.

To test the matter further the distance from A to ee' was made 12 cm., and the size of DD' was reduced to 2 cm. in diameter. There was then no discharge to CC' that could be detected. But this on the other hand did not prove that there was no emanation, since the emanation might quickly lose its power of producing ions.

To test this still further the cylinder was divided 6 cm. above A and the upper part insulated from the lower. The lower one about the wire was kept at the same potential as before but the upper was kept at the potential of the wire, so that there was no field in this part to draw the ions. If, however, the effect was due to some kind

of emanation, this emanation would lose its power of discharging as soon as before. It was found that with the conditions as described we again had a discharge to CC'. This discharge ceased as soon as the middle cylinder was raised to the same potential as the outer cylinders. This showed conclusively that the cause of the discharge in this case was something which could be destroyed by an electric field. It does not prove that there was no emanation whatever having a very brief period of activity, but it shows that we have no evidence of such emanation. Moreover I was not able by any method with which I am acquainted to show the existence of such emanation.

The cause of the decrease in the velocity of the positive ions will be considered after the fourth method of finding the velocity of the ions has been discussed.

Fourth Method.—The last method was one which has been employed by Rutherford.[1] It depends on the distance from the wire to which ions will pass under the action of an alternating potential difference. There are not as serious difficulties to be incurred in applying this method to the hot wire as there were to the arc. There are no such irregularities in the potential about the wire as there are about the arc. Nevertheless I have not been able to find a mathematical solution determining the distance to which ions will move under the influence of a given alternating potential difference. When the number of ions between the two cylinders is so small that the potential gradient is not affected by their presence, the distance can be easily computed. But the matter is very much complicated when there are many ions present, and even if a solution could be found where only one kind of ion is present, it would help but little when both kinds of ions are present.

Ordinarily the solution for the negative current can be superimposed on that for the positive and it gives the solution for the two combined, but here when the positive ion comes in contact with a negative one, the two combine and the effect of the two combined is not the same as that of the two separate. When separate one would move a certain distance in one direction and the other a different distance in the opposite, the relative distances depending on

[1] Proc. Camb. Phil. Soc., 9, 401.

the relative velocities. When combined they would not move at all. The resultant effect of the two combined, would, therefore, be different from the resultant of the two when separate. A combination of solutions for the positive and negative ions would not give a solution for the two. These difficulties taken in connection with the fact that the velocities of the ions appear to diminish according to some law not definitely known and that we are dealing with several different kinds of ions, make a mathematical discussion of question impossible.

But while this method can not here be used to determine the absolute velocities of the ions, it may be used to compare the relative velocities. The comparison which it affords is one between the most rapidly moving of the positive and the most rapidly moving of the negative ions.

The first set of observations were made with a cylinder 9 cm. in diameter and 3 cm. wide. A wire similar to those which have been used in the previous work was placed at the center of this. The current passing through the wire was measured by an alternating current ammeter and was 6.5 ampères. Thus it is evident that both positive and negative ions were being produced. The current was given by the secondary of a transformer which was part of the village lighting system. The potential of the wire was varied by the same method that has heretofore been used. The square root of the mean square of the potential of a point at the middle of the platinum wire was found by means of an electrometer connected idiostatically. There were 130 alternations of the current per sec.

It was found that in every case the surrounding cylinder became charged positively. This of itself was sufficient to show that the more rapidly moving of the positive ions have a greater velocity than any of the negative.

To determine the potential difference necessary to cause a discharge to pass to the cylinder, the rate was observed at which the cylinder became charged when different potential differences were used. Table XII. gives the deflection of the electrometer needle in four seconds with different potential differences. Column 1 gives the potential differences and column 2 the corresponding deflections.

TABLE XII.

Potential Difference.	Deflection of Electrometer.	Potential Difference.	Deflection of Electrometer.
49	5	26	.5
43	3.5	15	.0
35	2.4		

A curve was plotted from the data here given and it was assumed that the discharge ceased at the potential difference indicated by the point at which this curve crossed the line of zero discharge. In this case the potential difference thus indicated was 23 volts.

Similar sets of observations were taken with cylinders 5 cm. and 12.5 cm. in diameter. In the former case the potential difference necessary to produce the discharge was 9 volts and the latter 38 volts.

Causes of Decrease in Velocity of Ions.—We have seen that there are reasons for believing that the average velocity of the positive ions decreases at the higher temperatures. When we attempt to suggest a cause for this decrease, there are two explanations which present themselves. One explanation would be that a new kind of ion is being produced at the higher temperatures. During most of the time that I was investigating the subject I considered this to be the correct explanation, and expressed this idea in a short article in Physikalische Zeitschrift.[1] I was led to this conclusion by the fact that at higher temperatures the gas about the wire becomes ionized. If, moreover, one were to suppose that the ions of the gas move more slowly than those coming from the metal, an explanation of the decrease in the velocity of the ions at higher temperatures is at hand.

The fact that the negative discharge began at about the same temperature as that at which the gas about the wire became ionized also seemed to show that a new kind of ionization was being produced.

I have as yet no proof that such action as this may not be taking place, but experiments to be immediately described point to a different explanation of the phenomena, namely, that the same kind of ions are being produced at higher temperatures as at lower, but that

[1] Physik. Zeitsch., 25, 3, 158.

at the higher temperatures they are loaded with particles that are sent out from the glowing platinum. It is well known that minute drops of water will diminish the velocity of the ions on which they condense. There is no reason why matter from glowing platinum should not do the same. It is also known that glowing platinum diminishes in weight[1] and that it acts as nuclei for water condensation.[2]

The experiment which points to this as being the correct explanation was one on which I stumbled while investigating the discharge in other gases than air. It was found that the discharge in CO_2 was very much smaller than I had expected it to be. In fact it was so small as to indicate a velocity of only .025 cm. per second for a potential gradient of 1 volt per cm. This was most surprising, since the velocity of ions produced by X-rays in CO_2 was approximately the same as that of ions produced in air by this means. In attempting to find some error in my measurements it was found that the discharge to a metal cylinder enclosed in a glass tube was very much smaller than it was to the same cylinder when not enclosed. The glass cylinder was carefully insulated and the insulation tested until it was certain that this decrease was not being caused by leakage to the ground.

It was then found that the rate of discharge in the enclosed cylinder was by no means constant. When the wire was first heated the discharge was large, but decreased from its first value rapidly. When the wire was heated only to red heat the rate of discharge within the tube was nearly as large as it was in the open air, and at this temperature it diminished but very little after it had heated for some time. When it was heated to a higher temperature it diminished very rapidly and the final rate of discharge was not more than 3 per cent. of what it was to the same cylinder when not enclosed in the tube.

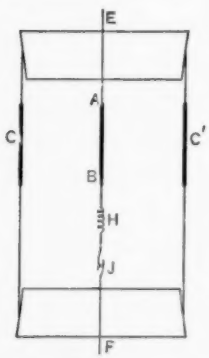


Fig. 5.

Apparatus.—These experiments were performed in a glass tube 24 cm. long, and 4.4 cm. inside diameter, closed at the ends with

[1] Wied. Ann., 31, 448.
[2] Nature, 31, 268.

rubber stoppers as shown in Fig. 5. The wire passed through the stoppers, the part between A and B being platinum. About AB was the cylinder CC'. This was 4 cm. in diameter, and 5 cm. long. H is a coil in the wire to keep AB straight. I is a hook at which the wire can be separated when it is desired to remove it. G is an opening to an air pump. The cylinder CC' was of tin.

A series of observations with different amounts of current flowing through the wire is given in Table XIII. The potential difference between the wire and the cylinder was 40 volts. Column 1 gives the time which elapsed from the starting of the current through AB to the time at which the discharge was observed, or more correctly, to the time at which this observation was commenced. Column 2 gives the positive discharge in 10^{-10} ampères when 4 ampères passed through the wire. The other columns give the rates of discharge with other amounts of current through the wire. The last two columns show the rates at which the negative discharge decreases. The rates of discharge were computed from the deflection of the electrometer needle, the length of time it was receiving the discharge and the capacity of the system.

TABLE XIII.

Time.		4 Amperes.	4.5 Amperes.	5 Amperes.	5.5 Amperes.	6 Amperes.	—6 Amperes.	—6.5 Amperes.
Minutes.	Seconds.							
	0	16	18	7.5	7.5	3.3	8.3	3.9
	20	14	10.8	4.6	4.1	2.8	2.3	1.9
	40	14.5	10.2	4.1	2.2	2.2	1.7	1.1
1	00	14	8	3.9	1.9	2.2	1.1	1.4
1	20	14	7.5	3.9	1.9	2.1	.8	1.1
1	40	14	6.6	3.9	1.4	2.2	.9	1.2

In taking the readings the air within the tube was changed after each set before the discharge with a different current was commenced. The rate at which the discharge decreased was quite different at different times. The data given in Table XIII. were taken with dry air and the wire heated for some time to remove any impurities. The smallest value given here for the positive discharge indicates a ve-

locity of only .12 cm. per second for unit potential gradient as compared with 4 cm. in the open air.

This condition of the gas within the tube existed for some time. Data bearing on this point are given in Table XIV. Six ampères were passed through the wire for some time, the circuit was broken for the length of time indicated in column 1, and then 4 ampères were sent through the wire and the rate of discharge noted. Four ampères is not sufficient of itself to produce this kind of "emanation" to an amount that could be detected by the electrometer. It could thus be used to test the condition of the gas. Column 2 gives the rate of discharge.

TABLE XIV.

Time.		Rate of Discharge.	Time.		Rate of Discharge.
Min.	Sec.		Min.	Sec.	
	0	4×10^{-10}		40	10.0×10^{-10}
	10	3.8 "	1		10.6 "
	20	7.2 "	30		12. "
	30	8.0 "			

After the tube had been opened and then closed again the rate of discharge was 14×10^{-10} ampères. The discharge with the ends of the tube open was 50×10^{-10} ampères.

There can thus be no doubt but that matter in some form is driven off from the glowing platinum and that this greatly retards the velocity of the ions when the gas is confined in the tube. This would also appear to be the cause of the smaller velocity of the ions in the open air at the higher temperatures.

The mere presence of particles driven off from a hot wire is more definitely shown by their use as nuclei for condensation to which reference has been made. A few experiments of this character were performed. The ordinary means of doing this were used. Air was drawn through a tube containing cotton wool soaked in glycerine. When the tube containing the wire was connected to an air pump from which the air had been nearly exhausted the formation of fog was plainly seen after the wire had been heated. When the air was suddenly drawn out three or four times no condensation was visible, until the wire was again heated.

It was found that two ampères sent through the wire were sufficient to produce condensation that was clearly visible. This was with a wire that required 3.5 ampères to produce any discharge that could be detected, and four ampères to become self-luminous.

With larger currents the fog became more dense but no attempt was made to take any measurements with it.

The most interesting experiments were those showing the length of time that the particles were suspended in the air. The tube could be left for several minutes after the wire had been heated and the condensation then produced appeared to be as dense as ever. When an hour passed before the fog was formed, it was found to be still plainly visible. At the end of two hours after the wire had been heated the condensation was barely visible. When the wire was heated and allowed to remain over night before the air was drawn out of the tube no condensation could be seen.

Another positive proof that matter is given off by the wire is shown by the loss of weight of the wire. With the size of wire here used no loss of weight could be detected when it was heated with five ampères for one hour. But when 6.2 ampères were passed through a piece weighing. 2888 grams for one hour, it lost .0013 gram.

There is of course nothing new in the fact that particles are driven off from a hot wire, but as far as I know no one has ever suggested the idea that these particles check the discharge from such wires. In fact the opposite has been suggested, namely that the discharge is carried by these particles. Such an idea would appear to be incorrect. The air which is enclosed and which consequently contains a greater number of the particles is the air which shows the slowest rate of discharge. Instead of aiding, the dust particles retard the motion of the ions, and may in an enclosed space almost entirely stop the discharge.

Experiments showing the behavior of the discharge in other gases than air and some bearing on the nature of the emanation will be given in the second part of the article.

It was stated at the beginning of this article that the rate of discharge increased when the wire was heated for some time. This no doubt is due to a diminution in the number of particles about the wire. It may be that the convection currents become stronger and

carry away the particles, or possibly there are fewer particles driven off after continued heating.

Summary.—The discharge from a hot platinum wire at first decreases and then slowly increases.

The positive discharge commenced a little below the temperature of red heat, increased at first rapidly as the temperature was increased, remained nearly constant through quite a range of temperature and finally decreased somewhat. The negative discharge began at nearly the same temperature as that at which the positive began to decrease. It never became as large as the positive.

Both positive and negative discharge increased rapidly as the potential difference between the wire and cylinder was increased.

Four methods were used for comparing the velocity of the positive and negative ions. One of these compares the average velocity of one with that of the other. This showed the velocity of the positive to be the greater. Two methods compare the velocities of the most rapidly moving of the positive ions with the most rapidly moving negative. Both of these show the positive ions to have the greater velocity. One compared the slowest of the positive with the slowest of the negative. This showed that at the lower temperatures the slowest of the positive ions have a much greater velocity than the slowest of the negative, but at higher temperatures a slower class of ions are produced, and the comparison of these with the slowest negative ions gave no definite results.

It was also found that at a certain temperature ionization is produced in the gas about the wire to greater than molecular distances. This is nearly the same temperature as that at which the negative discharge commences, as that at which the positive discharge materially decreases, and as that at which the very slowly moving positive ions commence to appear.

Experiments on a wire enclosed in a glass tube indicate the presence in the tube of particles which diminish very greatly the velocity of the ions. This "emanation" appears to load the ions and thus to diminish their velocity both when they are within an enclosed tube and when they are in the open space. Thus the particles driven off from a hot wire do not appear to aid in the discharge but to materially check it. This will be further discussed in the second part of this article.

A NEW FORM OF CAVENDISH BALANCE.[1]

By G. K. Burgess.

THE sensibility of Cavendish's method for the determination of the gravitation constant would be much increased if, while still preserving heavy masses hung from the balance arm, the tension which this weight exerts on the suspension wire could be suppressed. This possible, nothing would prevent realizing a measurement as sensitive as might be desired; the attraction between the two systems of spheres—the fixed and moving systems—would remain a definite quantity and allow increasing the deflection of the movable system by reducing more and more the diameter of the torsion wire. The principle that we have made use of with this object in view is the following: Compensate for the weight of the turning system by a float immersed in a mercury-bath; eliminate any capillary action that may tend to hinder the mobility of the system, and if then the zero remains constant, we have at our disposition an instrument of unlimited sensibility.

The dimensions of such an apparatus will be subordinated to considerations of precision, and ease of length measurements. If the dimensions are too large no gain in accuracy will be had; on the contrary the effects of temperature variations will be increased. On the other hand, with too small dimensions, exact measurements of length will be more difficult, and eccentricity effects increased.

We chose a length of 12 cm. for the lever-arm—a length easy to measure by the dividing-engine and not necessitating a large apparatus. From the two ends of the balance-arm are hung two lead spheres of 2 kg. each; the whole is buoyed by a cylinder immersed in mercury, whose surface is covered by dilute sulphuric acid; a rod passing through the mercury and acid connect the cylinder to the balance. The points of support for the spheres are below the center of inertia of the system, thus giving to the balance-

[1] Summary of Thesis, Recherches sur la Constants de Gravitation, Paris, 1901.

arm the form of three sides of a rectangle. Thanks to this arrangement, the torsion fiber has to support only a weight of 5 or 10 grams, instead of having to hold up a weight of 5.5 kg. and this difference allows of using a fine quartz fiber.

The attracting masses—two lead spheres of 10 kg. each—were hung from an independent support, and turned in a circle of radius of 18 cm.

The mobility of the suspended system was first carefully verified by a series of preliminary experiments. The liquid surfaces must be clean, and then as in the case of the Lippmann electrometer, the liquid surfaces were found to be mobile with respect to the glass surface of the supporting rod.

Great care had to be taken to obtain a constant zero which might be influenced by convection currents in the mercury and in the air. The *sine qua non* of this adjustment is a constant temperature throughout. We succeeded in establishing a uniform action of the mobile system only with the greatest care and only after the apparatus had been mounted several days.

Happily, as it was greater than one hour, we did not have to determine the exact period of oscillation of the system; it was sufficient to know the torsion coefficient of the fiber, established by preliminary experiments with an auxiliary cylinder, and determine the deflections of the system under definite conditions.

In our apparatus it was not necessary to place the attracted spheres at different levels to increase the sensibility. In fact, the apparatus as we constructed it, used in the most sensitive manner, gave deflections exceeding 1 meter on a scale at 2.6 meters distant.

All parts of the apparatus were symmetrically arranged about the central axis, in order to avoid corrections arising from secondary attractions. The total force of attraction was of the order of 0.01 dyne.

Besides a gravimeter, our apparatus might become accidentally both magnetometer and electrometer, thus introducing sources of error due to magnetic or electrostatic attractions. These effects were carefully tested for and eliminated.

Apparatus.

The apparatus was installed in a cellar of the Physical Research Laboratory at the Sorbonne, and mounted on a stone pillar 1 m. × 1 m. × 0.5 m. The stability conditions were sufficiently good especially at night. As to temperature variations they were a minimum : less than 0.1° C. a day, and with the change of season from winter to summer, the temperature of this cellar rose less than two degrees in three and a half months.

As to the construction of the apparatus : the four lead spheres were turned on a heavy lathe from cylinders cast with great care taken to leave them homogeneous. Their supporting wires, arsenical bronze for the mobile system and piano steel for the others, were

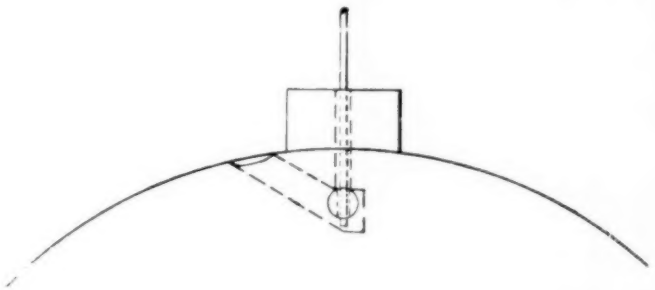


Fig. 1.

attached as shown in Fig. 1. The lead knob was equivalent in mass to the excavated portion of the sphere, and the wire was held by a small brass sphere.

The balance-arm which supported the 2 kg. masses was of aluminium bronze (7 per cent. aluminium) and of the form indicated in Fig. 2. The horizontal arm was 12 cm. long, the vertical arms 9 cm. Lead compensating weights adjustable in position were placed at the ends of the horizontal arm. Immersed in a glazed earthenware cylindrical vessel filled with mercury was a varnished hollow copper cylinder of such volume that the weights of the two spheres joined to the auxiliary weights of the balance and cylinder about equaled the weight of displaced mercury.

The cylinder was attached to the balance by a steel rod of 2 mm. diameter which was covered by a thin glass tubing from the top of the cylinder to the balance-arm, for protection against the acid layer on the mercury surface.

The earthenware vessel—12 cm. high and 9.5 cm. diameter—containing about 7 kg. of mercury, rested upon a brass plate, carried by a brass pillar movable vertically and in azimuth. This pillar was screwed into a massive circular base also adjustable in azimuth

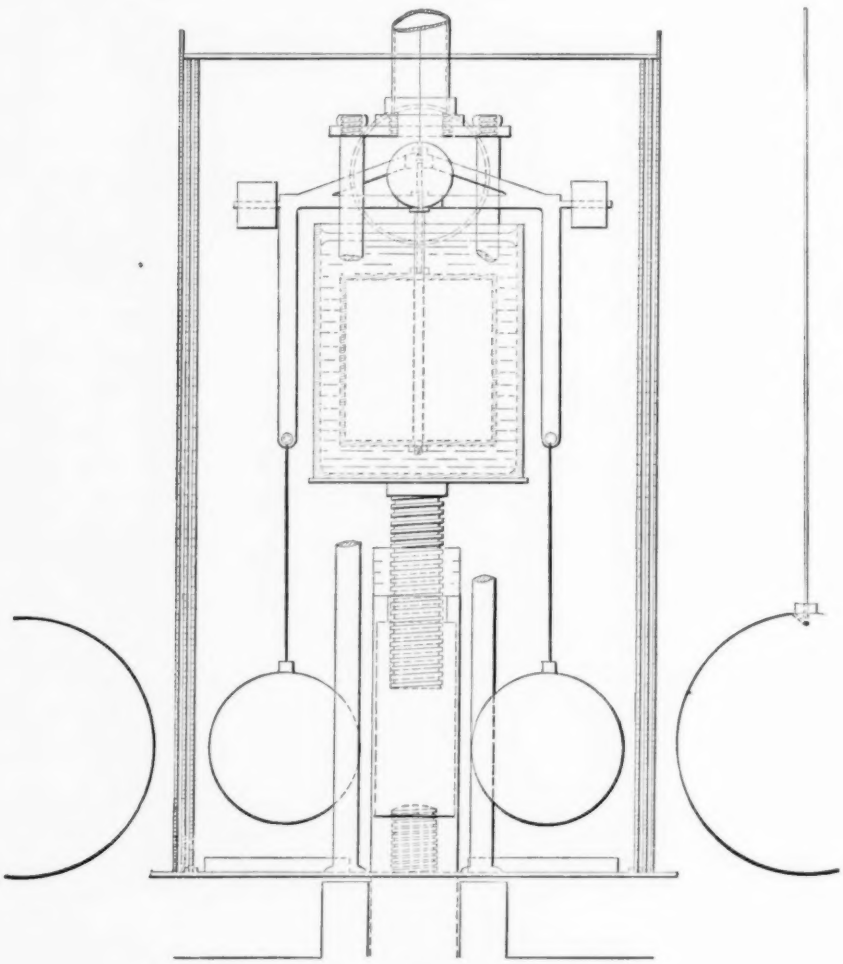


Fig. 2.

mounted on three legs with leveling screws, and carrying on the outer circumference of 24 cm. diameter a divided circle which served to measure the angles turned by the large spheres. The torsion fiber of quartz 35 cm. long and 0.03 mm. diameter passed through

a glass tube with a torsion head permitting independent vertical and azimuth movements. Two brass pillars, nearly at right angles to the plane of the balance arm, carried a brass plate into which was screwed the torsion tube. Adjustments were provided to center the fiber into the axis of symmetry of the apparatus. The mirror was plane and circular of 2.5 cm. diameter.

The support for the large outer spheres, completely independent of the inner system, consisted of a heavy oak triangular frame, carrying at its top a centrally mounted bronze arm, one end adjustable longitudinally and the other laterally, from which were hung the large spheres, adjustable vertically, so that the horizontal and vertical eccentricities of the two systems of spheres could be easily rendered a minimum.

The inner system was surrounded by a glass cylinder 20 cm. in diameter, and two of cardboard separated by a layer of sawdust. The large spheres were without this, but the whole was enveloped by a covering of thick black cloth tacked to the oak frame.

A glass window having plane faces permitted observation of the mirror with a telescope placed at 3 meters distance having a 5 cm. objective and a magnifying power sufficient to read $\frac{1}{20}$ mm. on the ground-glass scale at 2.6 m. from the apparatus. The scale was illuminated by an incandescant lamp lighted only during the instants of reading.

The dividing engine used to measure the horizontal dimensions of the apparatus by means of a small telescope mounted on the carriage was from Perreaux. Its screw was 60 cm. long, whose average pitch served as the standard of length, which compared with a Sevres meter gave 0.9998 cm. of the screw equal to 1 cm. international. Vertical distances were measured with a cathetometer reading to 0.02 mm.

An aluminium cylinder of 30.060 grm. served to determine the torsion coefficient of the quartz fiber. The ratio of its diameter to height was $1 : \sqrt{3}$ so that its ellipsoid of inertia was a sphere. This arrangement has the advantage that if the axis of suspension does not traverse the center of inertia of the cylinder, the moment of inertia rests constant.

A steel tape mounted on a board set on edge was used to measure the distance from the mirror to the scale.

THEORY.

To determine the gravitation constant, with such an apparatus, the following is the geometrical theory to a first approximation.

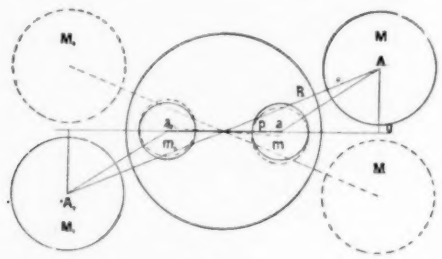


Fig. 3.

Let M and M' be the masses of the two large spheres turning about the axis of the system with radius R; m and m', the two spheres hung on the balance arm of length $2r$; $\overline{Aa}$, the distance from a large to a near small sphere; γ the torsion moment; then the attraction of M or m is:

$$MmK/\overline{Aa}^2.$$

The torsion moment:

$$\gamma = MmK \cdot \overline{Aur}/\overline{Aa}^3 = MmKRr \sin \varphi/\overline{Aa}^3.$$

But

$$\overline{Aa} = (R^2 + r^2 - 2Rr \cos \varphi)^{\frac{1}{2}}.$$

Therefore

$$\gamma = MmK \cdot Rr \sin \varphi(R^2 + r^2 - 2Rr \cos \varphi)^{-\frac{3}{2}}.$$

For the attraction of M or m', we have similarly:

$$\gamma' = Mm'K \cdot Rr \sin \varphi(R^2 + r^2 + 2Rr \cos \varphi)^{-\frac{3}{2}},$$

and for that of M' on m' and of M' on m there are analogous equations. The angle φ is composed of two parts

$$\varphi = \theta - \alpha,$$

where θ and α are the angles made by the attracting and attracted spheres with their respective equilibrium zero positions.

In an actual computation the formulæ are not quite so simple for two reasons: the eccentricity of the mounting with respect to the cen-

tral axis and the differences of level of the several spheres give rise to trigonometrical corrections easy to calculate.

The mean density of the earth Δ may be calculated from the gravitation constant K, independently of the local value of g as follows:

$$g = \tfrac{4}{3}\pi R_p \Delta K(1 + a - \tfrac{3}{2}c)\{1 + (\tfrac{5}{2}c - a)\sin^2\beta\}$$

where R_p is the polar radius, a the flattening of the earth, c the ratio of centrifugal force to that of gravity at the equator, and β the latitude.

Measurements.

Let us consider briefly the series of measurements and operations necessary to determine the gravitation constant with this apparatus.

The constant of torsion of the fiber was first determined in an auxiliary mounting by means of an aluminium cylinder. Times were taken with a Breguet (3030) chronometer by the telescope and scale method. The dimensions of the cylinder measured by the dividing engine were as follows: radius 1.31405 ± 0.00059 cm., height 2.2519 ± 0.0012 cm., mass 33.060 grm. and its moment of

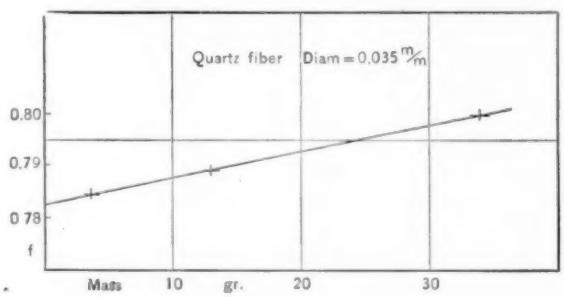


Fig. 4.

inertia 28.545 c.g.s. This latter, corrected for the knob of the cylinder, mirror and screw, was $I = 28.788$ c.g.s. units.

As the coefficient of torsion varies with the stretching force, the coefficient of the quartz fiber for any mass suspended was found by a series of auxiliary paraffine cylinders, with the results indicated in Fig. 4. Knowing the weight on the fiber in the gravitation apparatus, the proper coefficient was readily found by interpolation.

The torsion coefficient is given by $f = 4\pi^2 I/t^2$. For the quartz fiber used in three series, the preliminary determinations gave :

$$t = 51.''792 \pm 0.0005, \qquad f = 0.42367.$$

With the Aluminium Cylinder.

The gravitation apparatus was then set up with this fiber in place, and eccentricity of mounting was as nearly as possible eliminated by the adjusting screws. The zero position of the mobile system was then found and set to a convenient part of the scale. This operation took several days, for the system remained in motion so long as any disturbing cause persisted. In addition to the precautions taken to obtain constant temperature described above, numerous cardboard screens cut up into as small sections as possible the enclosed air space about the inner spheres.

When constancy of zero was obtained the outer spheres were hung in place and a series of measurements was taken, extending over several days, of the deflections of the inner system of spheres in response to the definite and subsequently measured positions of the outer attracting spheres. In general it took over two hours for the inner system to take up a very small oscillation about a new position. The period was one hour, ten minutes. The constancy of a given position is illustrated by the following, taken from the second quartz series, for three successive deflections to the right on as many days taken alternately with deflections to left :

72.205 cm.
72.318
72.135

Five minute readings were taken for four or five hours for each position. The total deflection was about 65 cm. on a scale at 2.6 m. The measurements of deflection taken, the distance from the suspension to the scale was measured, and after removing the coverings the horizontal distances between the various spheres and the torsion fiber were determined with the dividing engine placed parallel to the balance arm at 40 cm. distance. This gave the data also for horizontal eccentricity. Similarly, the vertical distances between the centers of the spheres were taken with the cathetometer, giving

vertical eccentricity corrections. The horizontal eccentricity perpendicular to the plane of the balance was also measured, and also the angles formed by the right and left and ventral positions of the outer spheres by means of the graduated circle at the base of the apparatus and the telescope and scale. During these measurements, taken in the zero position of the inner system, the smaller spheres were kept in place by stops. Phosphor-bronze was also tried as suspension but its zero is by no means constant enough for this kind of work.

For three series with the same quartz fiber, whose constants are given above, the following are the principal data for the determination of K.

	R_1	R_2	r_1	r_2	Dis Scale to Suspension.
Series I.	18.359	18.060	6.158	6.144	260.80
" II.	17.950	18.630	6.212	6.121	260.15
" III.	18.149	18.506	6.188	6.144	260.14

	Deflections = Attracted Masses		Deflections = Attracting Masses.		Torsion Factor
	Right	Left	Right.	Left.	
Series I	2° 16′.09	4° 6′ .75	11°.35	28°.67	0.9812
" II.	2° 05′.11	4° 20′.62	13°.13	26°.90	1.0000
" III.	2° 05′.15	4° 48′.50	11°.47	28°.56	0.9811

There are four equations of this form to solve for each series:

$$K = f\frac{[R^2 + r^2 \pm \cos(a - \varphi)]^{\frac{3}{2}}}{MmRr \cdot \sin(a - \varphi)} \quad \text{where} \quad f = \frac{\gamma\pi\varphi}{180}.$$

Solving, gives $K = 6.64 \cdot 10^{-8}$ and $J = 5.55$.

The measurements were so planned as to give a precision of 0.001 in the final result. The separate quantities were all determined to 0.0003, with the exception of $(a - \varphi)$. This precision required a knowledge of the horizontal distances R and r (see Fig. 3), as measured on the dividing engine, to 0.002 cm. for the lesser and to 0.005 for the greater radius; the dimensions of the auxiliary cylinder to 0.002 cm., and its time of oscillation to 0.08 sec. only. This time was actually determined to 0.001 sec. and a precision

double that required in the length measurements was attained. The constancy of the deflection reading was the gravest source of error. The angles should be known to 0′.4. It had to be assumed that the elastic properties of quartz were perfect or at least that there is no change in the zero position. This assumption seems justified from the work of Threlfall and Pollock with their quartz fiber gravity balance.

The necessary tests and corrections for the use of the telescope-scale-mirror method were made as indicated by Holman.[1]

The results thus far obtained are to be considered only as tentative, and indicative of the possibilities of the method.

The apparatus may be improved by :

1. Mounting it in vacuo, only a slight advantage here as periods are not measured.

2. Making the balance-arm 10 cm. a submultiple of the meter.

3. Turn the outer spheres automatically.

4. Render the temperature of the mercury more constant by enclosing in a vacuum jacket with thick inner copper wall.

5. Avoid any but a residual deflection measurement by turning the torsion head the necessary angle, calculated beforehand, to counterbalance the gravitation moment.

6. Take readings photographically.

7. Work out in the country.

The method possesses advantages which render it perhaps the best for a determination of the gravitation constant, such as :

The possibility of increasing indefinitely the sensitiveness as has been indicated.

The non-obligation to determine the period of the system.

The possibility of using a null-method—a great advantage, obviating troublesome convection currents.

Its adaptability—due to its great sensitiveness—to the study of the effects of various interposed media and attracting masses of different kinds, or in other words for detecting, if they exist, any modifications of Newton's law.

This research was carried out under the direction of Prof. Lippmann, and to him I am greatly indebted.

[1] Holman, Telescope-Mirror-Scale Method, Tech. Quarterly, Sept., 1898.

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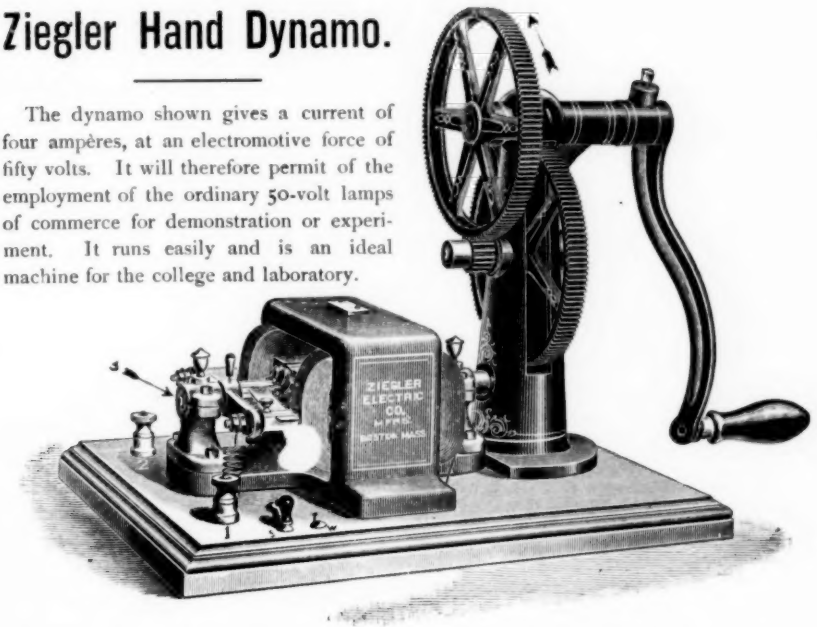

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